settled in the laboratory prior to the thickening tests as shown in Figure 1. The Cambridge CSO was settled in the detention tank itself and two separate samples were used for the thickening tests as shown in Figure 2. Bench-scale tests consisted of gravity, flotation, and centrifugation thickening.

The average quantities of sludge requiring dewatering treatment for the two sites were calculated to be approximately 131 cu m (34,700 gal.) and 68 cu m (18,000 gal.) on a per storm event basis (Table 2). The chemical clarification of Milwaukee (Humboldt Avenue) tank contents produced a residual with 1.74% solids while the sedimented residue samples obtained from Cambridge showed 4.4% and 11% solids for two separate samples. The flux concentration curves (see Appendix B for details of curve construction) for the gravity thickening tests for Milwaukee and Cambridge samples are shown in Figures 3 and 4. From these curves, it can be seen that for Milwaukee, the sludge could be concentrated to 6% solids at an allowable mass loading rate of approximately 45 kg/sq m/day (9 lbs/sq ft/day). The corresponding concentration level achieved for the Cambridge sludge was 14% solids with the more concentrated raw sample at 160 kg/sq m/day (32 lbs/sq ft/day) without any chemicals. The results of the flotation thickening tests for the two sites are shown in Figures 5 through 8. It was found essential to use flocculating chemicals (cationic polyelectrolytes such as Atlasep 105C and Dow C-41) to aid flotation. Optimum flotation thickening results were achieved at recycle rates between 300 and 600% and polyelectrolyte dosages between 1 and 3 kg/m ton (2 to 6 lbs/ton). Scum solids concentrations of 11 to 14% for Milwaukee and 6 to 8% for Cambridge sample (with the 4.4% solids raw sample) at the above mentioned optimum chemical dosages and recycle rates were achieved. The results of the centrifuge tests for the two storage tank residuals are presented in Tables 8 and 9. Again optimum results were achieved with the aid of the cationic polyelectrolyte, Dow C-41. Optimum solids recoveries were achieved at gravitational force between 700 and 1,000 G and spin time between 60 and 120 seconds. Cake solids between 30 and 35% could easily be achieved for both sludges under optimum conditions.

A summary of the estimated area and cost requirements of various dewatering techniques under optimum treatment conditions for the two storage/settling type treatment sites is shown in Table 10. The total annual costs shown in this table include the amortized capital costs, operating costs and the cost of hauling the ultimate treatment residuals to a landfill area. It is also assumed that the dewatered supernatant liquid can be discharged to the dry-weather treatment facilities. Additional details of the cost estimates are presented in Appendix C. For comparison, vacuum filtration treatment costs are also included based on engineering judgment and filter performance for other sludges evaluated in this study. Examination of Table 10 shows that centrifugation was the optimum dewatering process based on performance, area and cost requirements for both the storage treatment sites evaluated in this study.

Philadelphia, PA

As mentioned earlier, the backwash wastewaters produced from the micro-

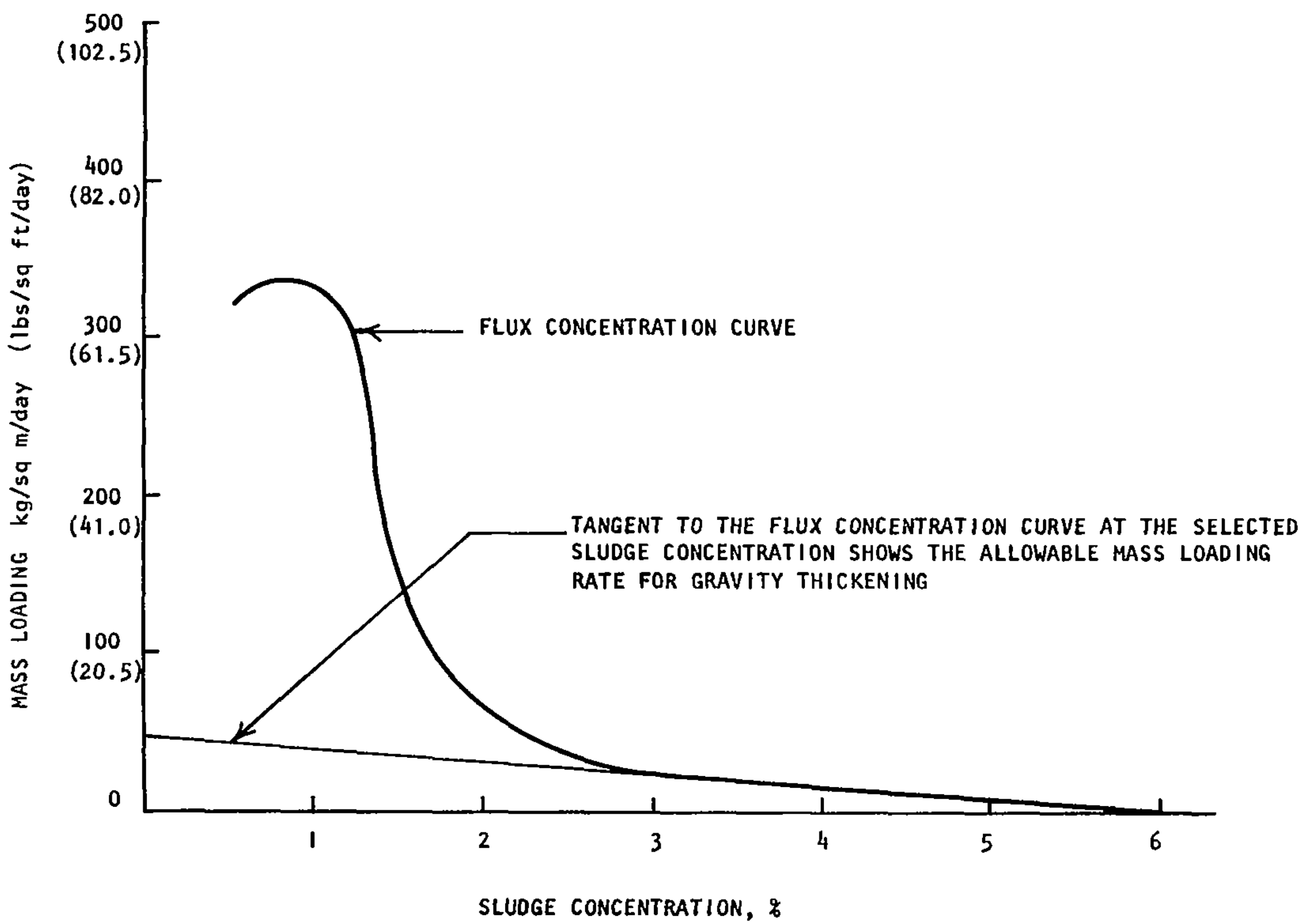

Figure 3. Flux concentration curve for Milwaukee (Humboldt Ave.) (storage/settling) sludge

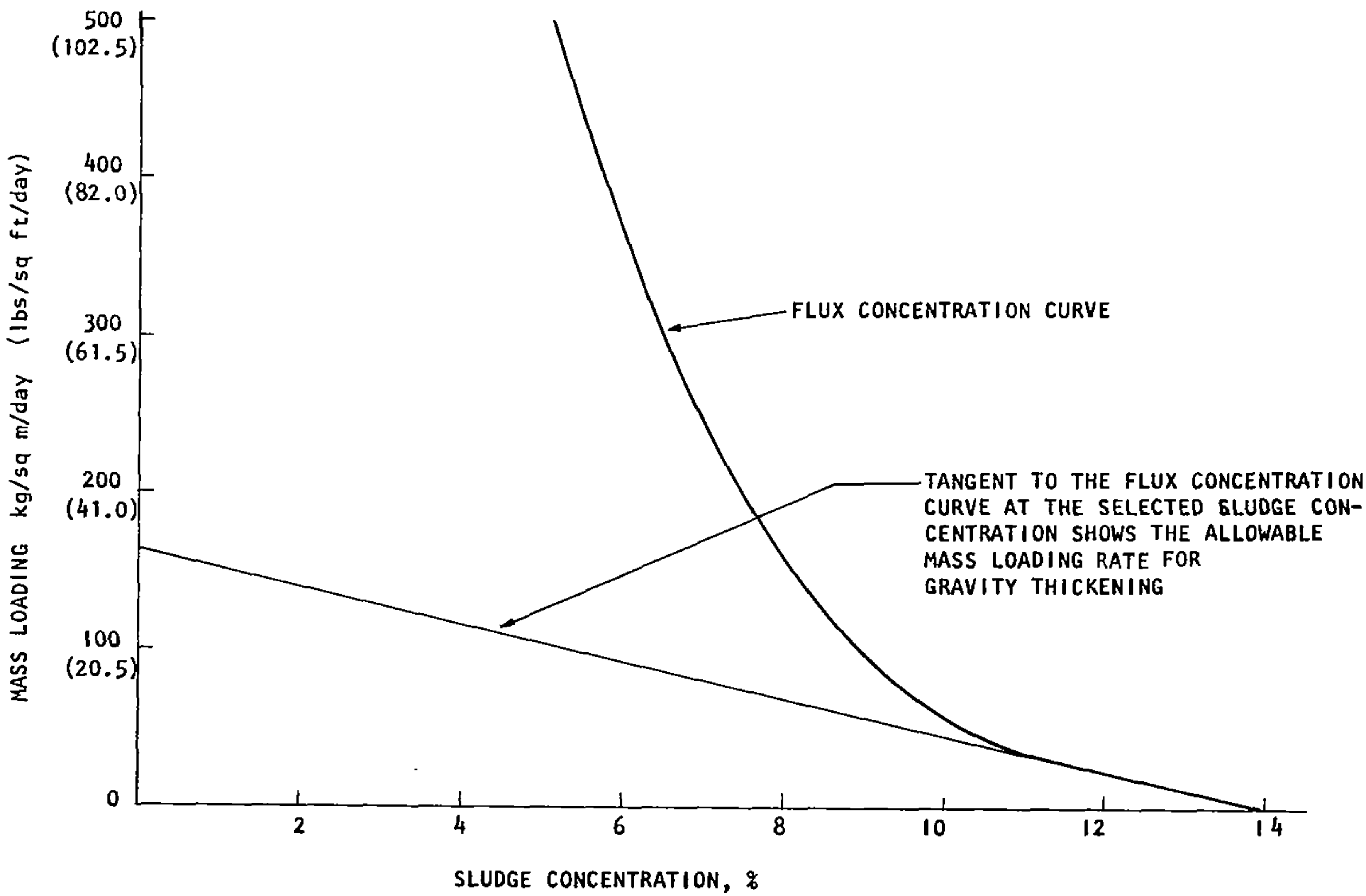

Figure 4. Flux concentration curve for Cambridge (storage/settling) sludge

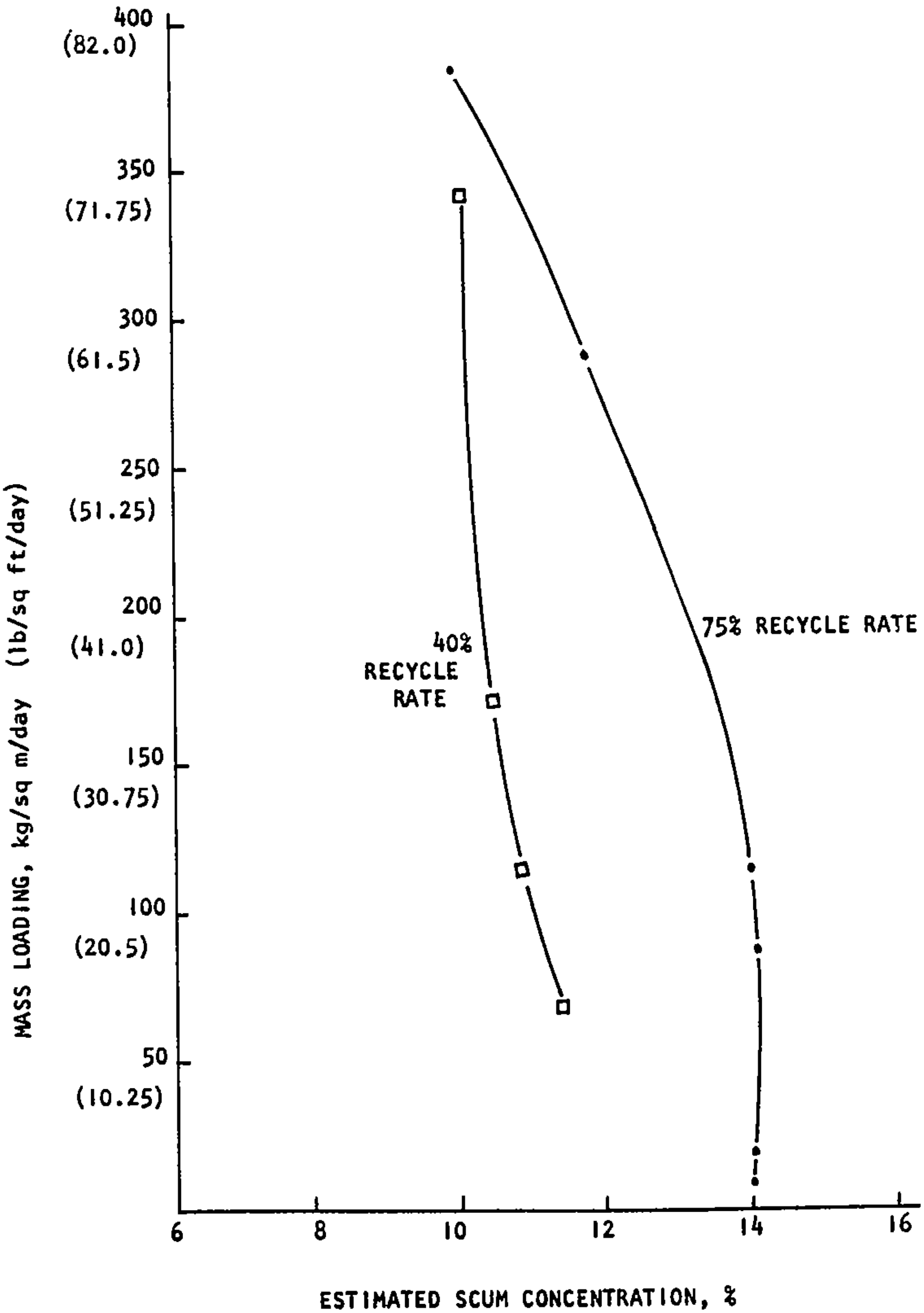

Figure 5. Flotation thickening results for Milwaukee (Humboldt Ave.) WI, storage/settling sludge - without chemicals

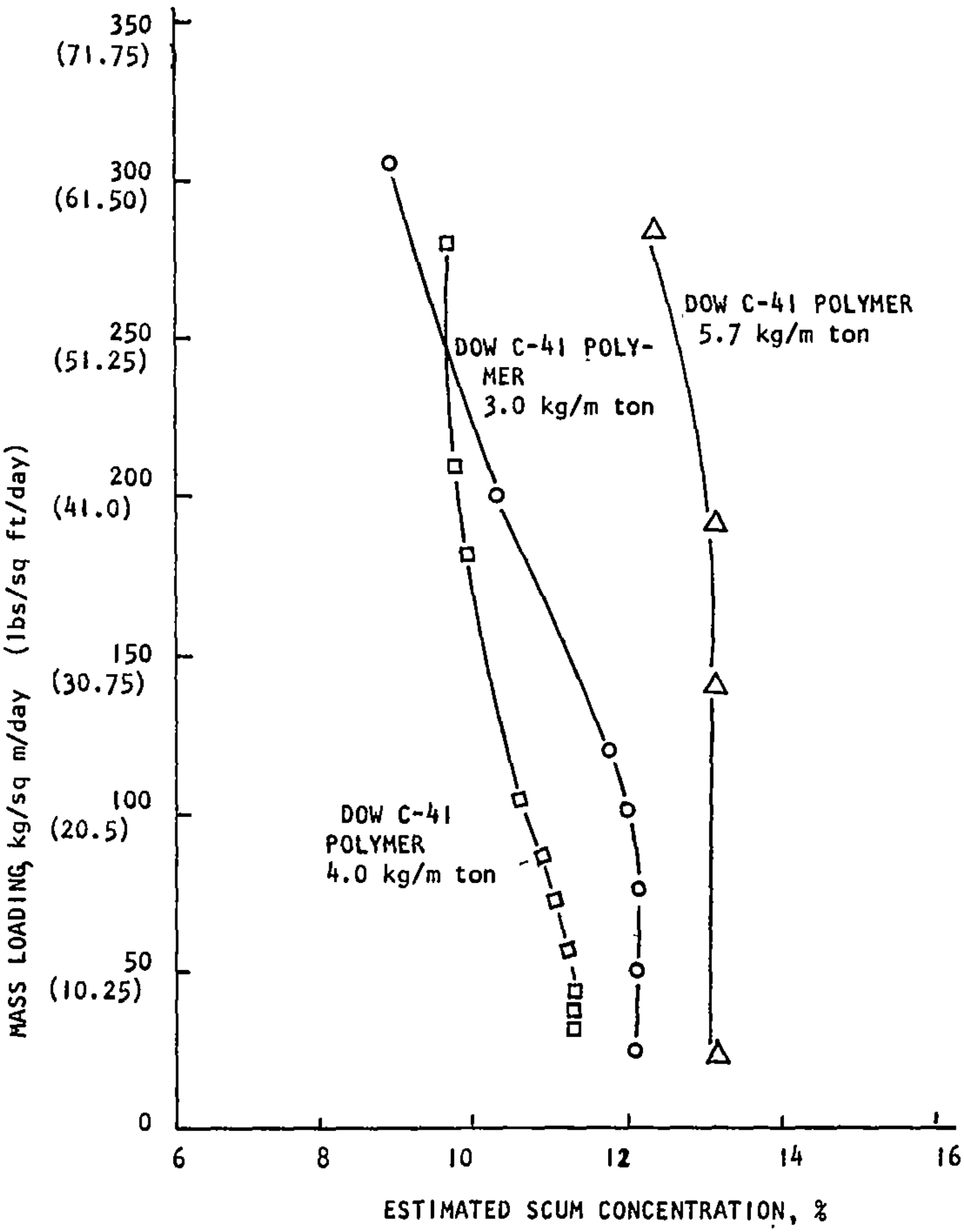

Figure 6. Flotation thickening results for Milwaukee, WI (Humboldt Avenue) storage/settling sludge-with chemicals (All tests at 290% recycle rate)

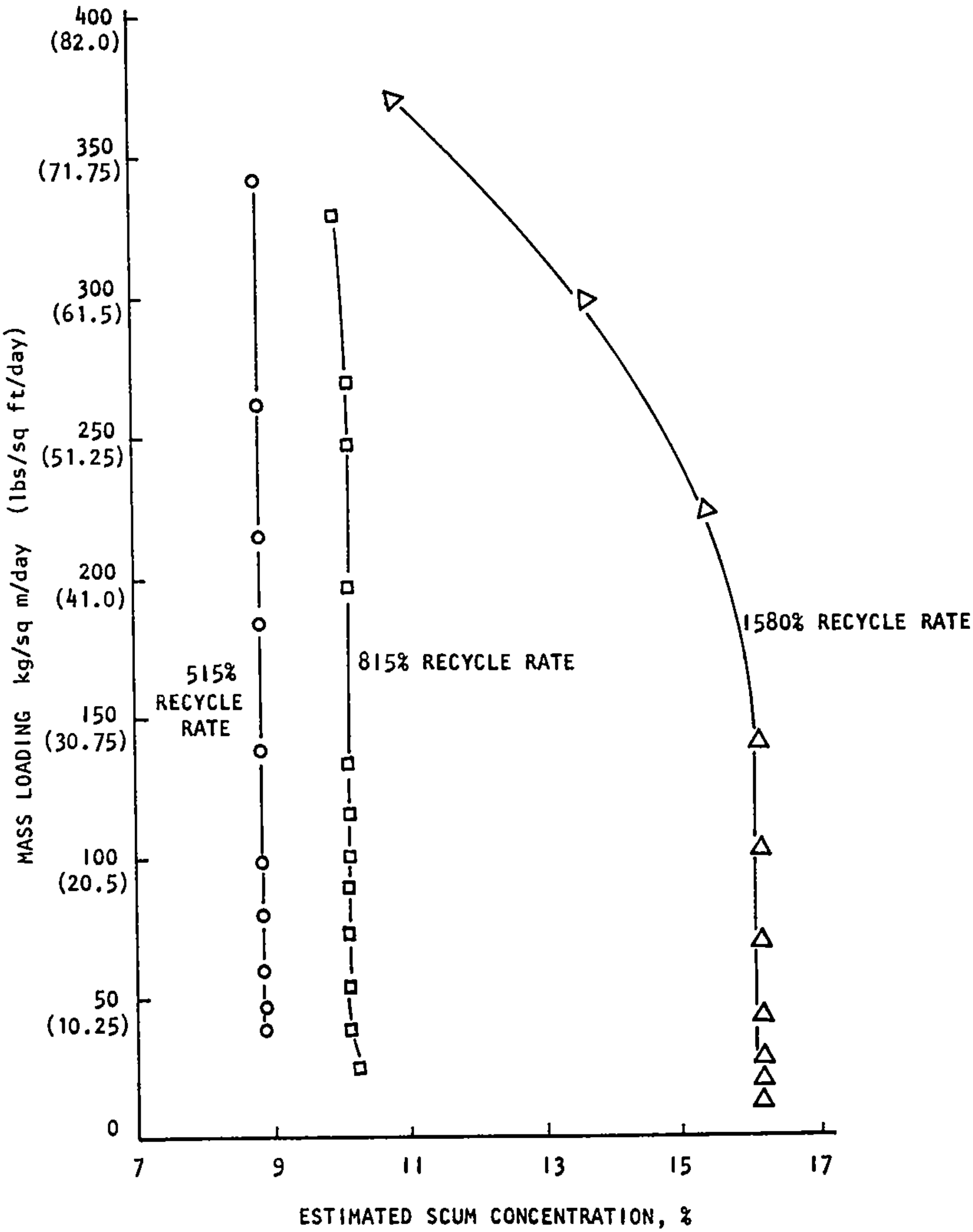

Figure 7. Flotation thickening results for Cambridge, MA storage/settling sludge-without chemicals

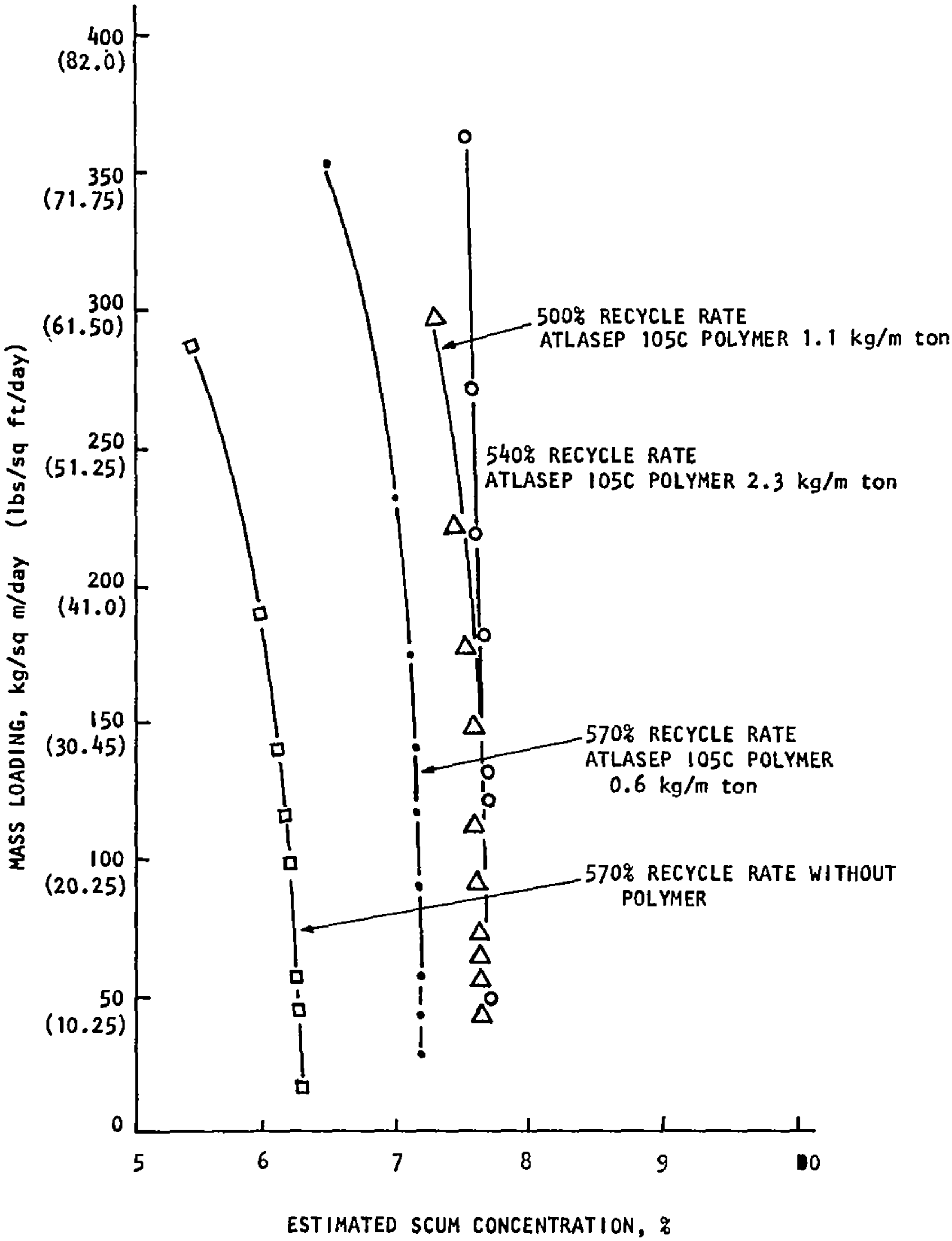

Figure 8. Flotation thickening results for Cambridge, MA storage/settling sludge - with chemicals

Table 8. CENTRIFUGE TESTING RESULTS FOR MILWAUKEE, WI, HUMBOLDT AVENUE, STORAGE/SETTLING SLUDGE

Test No.	Applied G force, G's	Time, sec	Feed solids, mg/l	Chemical	Dosage, kg/m ton	Centrate solids, mg/l	Centrate volume, ml	Penetration, cm	Sludge depth, cm	Cake solids, %	Penetration, %	Recovery, %	Corrected recovery, %
1	1,000	120	17,400	none	none	238	67	0.75	1.45	16.1	50	98.6	91.9
2	1,000	90	17,400	none	none	228	70	0.8	1.4	25.8	42	98.6	90.4
3	1,000	60	17,400	none	none	288	69	0.85	1.5	21.4	44	98.3	90.5
4	1,000	30	17,400	none	none	524	68	1.1	1.6	18.1	31	96.9	86 1
5	700	120	17,400	none	none	190	67	0.8	1.6	16.1	30	98.9	92.2
6	700	90	17,400	none	none	230	68	0.95	1.6	16.4	41	98.6	90.1
7	700	60	17,400	none	none	324	69	1.0	1.45	21.4	31	96 3	87.4
8	700	30	17,400	none	none	570	68	1.45	1.45	16.1	0	96 7	0[a]
9	400	120	17,400	none	none	326	69	1.55	1.55	21.4	0	96.1	0[a]
10	400	90	17,400	none	none	401	69	1.65	1.65	21 3	0	97.6	0[a]
11	400	60	17,400	none	none	605	66	1.75	1.75	14 1	0	96.5	0[a]
12	400	30	17,400	none	none	3,200	64	1.9	1.9	10.0	0	81.6	0[a]
13	1,000	120	17,400	C-41	3.4	119	71	0.4	1.4	32.4	71	99.3	95.9
14	1,000	90	17,400	C-41	3.4	119	72	0 4	1 35	43.2	70	99.3	95.8
15	1,000	60	17,400	C-41	3.4	107	71	0.45	1.6	32 4	72	99.3	96.0
16	1,000	30	17,400	C-41	3.4	121	70	1.6	1.6	25.9	0	99.3	0[a]
17	800	120	17,400	C-41	3.4	84	71	0.6	1 6	32.5	63	99.5	95.0
18	800	90	17,400	C-41	3.4	114	71	0.4	1.3	32 4	69	99.3	95.6
19	800	60	17,400	C-41	3.4	84	74	0.45	1.4	13.0	67	99.3	95.5
20	800	30	17,400	C-41	3.4	89	73	1.3	1.3	64.9	0	99.4	0[a]
21	600	120	17,400	C-41	3.4	90	74	0.5	1.4	13.0	64	99.4	95.0
22	600	90	17,400	C-41	3.4	151	71	0.65	1.5	32.4	57	99.1	93.6
23	600	60	17,400	C-41	3.4	155	71	0.65	1.6	32.3	60	99.1	94.1
24	600	30	17,400	C-41	3.4	134	69	0.9	1.55	21.6	0	99.2	0[a]
25	400	120	17,400	C-41	3.4	106	69	0.65	1.6	21.6	59	99 3	94.1
26	400	90	17,400	C-41	3.4	120	69	0.7	1.65	21.6	57	99 3	93.8
27	400	60	17,400	C-41	3.4	128	69	1.6	1.6	21 6	0	99.2	0[a]
28	400	30	17,400	C-41	3.4	129	68	1 8	1.8	18.5	0	99.2	0[a]

a. Indicates full penetration of the test rod through the thickened sludge and hence poor performance under the corresponding test conditions. See Appendix B for procedure.

Table 9. CENTRIFUGE TESTING RESULTS FOR CAMBRIDGE, MA, STORAGE/SETTLING SLUDGE

Test No.	Applied G Force, G's	Spin time, sec	Feed solids, mg/l	Chemical, Atlasep	Dosage, kg/m ton	Centrate solids, mg/l	Centrate volume, ml	Penetration, cm	Sludge depth, cm	Cake solids, %	Penetration, %	Recovery, %	Corrected recovery %
1	1,000	120	110,000	none	none	912	42	1.0	3.8	24.9	74	91.7	88
2	1,000	90	110,000	none	none	987	43	1.0	3.75	25.6	73	91.0	88
3	1,000	60	110,000	none	none	975	43	1.15	3.6	25.6	68	91.1	87
4	1,000	30	110,000	none	none	2,183	46	0.35	3.3	28.1	89	80.2	79
5	800	120	110,000	none	none	766	48	0.45	3.25	30.4	86	93.0	91
6	600	90	110,000	none	none	812	47	0.35	3.5	29.3	90	92.6	91
7	800	60	110,000	none	none	1,949	46	0.45	3.35	28.1	87	82.3	81
8	800	30	110,000	none	none	2,733	45	0.40	3.45	27.1	88	75.2	74
9	600	120	110,000	none	none	1,249	43	0.6	3.05	25.6	85	88.6	86
10	600	90	110,000	none	none	1,616	45	0.7	3.6	27.2	81	85.3	83
11	600	60	110,000	none	none	1,433	47	0.7	3.55	29.2	80	87.0	84
12	600	30	110,000	none	none	3,000	46	0.75	3.6	28.0	79	72.7	70
13	400	120	110,000	none	none	1,566	42	0.8	3.85	24.8	79	85.8	83
14	400	90	110,000	none	none	1,383	39	0.65	4.2	22.8	86	87.4	85
15	400	60	110,000	none	none	1,683	40	0.95	4.2	23.4	76	84.7	81
16	400	30	110,000	none	none	3,066	41	1.3	4.5	23.9	71	72.1	70
1	1,000	120	110,000	105C	0.18	515	49	0.55	3.2	31.6	83	95.3	93
2	1,000	90	110,000	105C	0.18	585	50	0.4	3.25	32.9	88	94.7	93
3	1,000	60	110,000	105C	0.18	810	49	0.45	3.4	31.6	87	92.6	91
4	1,000	30	110,000	105C	0.18	910	46	0.55	3.55	28.3	84	91.7	89
5	800	120	110,000	105C	0.18	580	47	0.3	3.4	29.4	91	94.7	93
6	800	90	110,000	105C	0.18	610	51	0.4	3.45	34.2	88	94.4	92
7	800	60	110,000	105C	0.18	735	49	0.55	3.35	31.6	84	93.3	91
8	600	30	110,000	105C	0.18	845	48	0.55	3.55	30.4	84	92.3	90
9	600	120	110,000	105C	0.18	780	44	0.55	3.6	26.5	85	92.9	90
10	600	90	110,000	105C	0.18	720	44	0.45	4.05	26.5	89	93.4	91
11	600	60	110,000	105C	0.18	735	46	0.5	3.65	28.3	86	93.3	91
12	600	30	110,000	105C	0.18	965	43	0.65	3.9	25.6	83	91.2	89
13	400	120	110,000	105C	0.18	830	47	0.5	3.8	29.3	87	92.4	90
14	400	90	110,000	105C	0.18	670	43	0.55	4.15	25.7	87	93.9	91
15	400	60	110,000	105C	0.18	855	37	0.85	4.7	21.6	62	92.2	90
16	400	30	110,000	105C	0.18	1,290	34	1.0	4.5	20.0	78	88.3	86

Table 10. SUMMARY OF AREA AND COST REQUIREMENTS FOR STORAGE/SETTLING TREATMENT RESIDUALS UNDER OPTIMUM TREATMENT CONDITIONS

Site	Humboldt Avenue				Cambridge			
	Sludge solids, %	Area sq ft	(sq m)	Total annual cost,[a] $/yr	Sludge solids, %	Area sq ft	(sq m)	Total annual cost[a], $/yr
Gravity thickening[b]	6	710	(66)	57,600	14	1260	(117)	37,900
Flotation thickening[b]	14	452	(42)	39,600	7	365	(34)	72,300
Centrifugation[b]	32	32	(3)	21,300	34	32	(3)	22,700
Vacuum filtration[b]	30[c]	140	(13)	26,700	30[c]	140	(13)	31,000

[a] Capital costs amortized for 20 year equipment life and 10% interest rate. For details of cost estimates, see Appendix C.

[b] All tests conducted after concentration of storage tank contents with sedimentation

[c] Comparative data based on assumptions of 95% solids recovery and yield of 15 kg/sq m/hr (3 lbs/sq ft/hr).

All costs based on December, 1974 prices.

screening treatment of CSO are quite dilute in nature and pre-concentration of these wastes is necessary prior to any dewatering. Because of the many difficulties experienced in collecting a suitable sludge sample from this site, a synthetic waste sample was produced for bench-scale dewatering tests by flushing the site drainage area with fire hydrant water. It was hoped that the waste sample produced would be similar to the actual screen backwash waste. However, only an extremely limited amount of concentrated sludge sample could be generated by the hydrant flushing and the data obtained was highly questionable. It was felt that any conclusions derived from such data would not be meaningful and may be misleading. Therefore, it was decided to omit the data from the treatment feasibility tests for this site. However, evaluations were conducted on the pump/bleedback concept for this wastewater, and are presented in Section VII of this report.

B. PHYSICAL/CHEMICAL TREATMENT

Three samples of residuals were obtained under this category of CSO treatment. Two of these samples were procured from screening/dissolved-air flotation treatment facilities in Milwaukee and Racine, WI. The third sample was obtained from the dissolved-air flotation treatment facility in San Francisco, CA.

Racine, WI

Two separate samples of the combined screen backwash and flotation scum from the sludge holding tank were obtained in Racine. A schematic of the various dewatering tests conducted on these samples is shown in Figure 9. The average quantity of the residuals (both floated scum and screen backwash) requiring handling and/or treatment on a per storm basis for the Racine facility is estimated to be 458 cu m (121,000 gal.) at a suspended solids concentration of 8,430 mg/l (Table 2). The flux concentration curve for the gravity thickening tests for Racine sludge is shown in Figure 10. The sludge settled extremely well with and without chemicals. Using the Coe and Clevenger (8) and Mancini (9) method of gravity thickening analysis, underflow concentrations greater than 15% solids could be expected at extremely high solid loading rates in excess of 2,000 kg/sq m/day (400 lbs/sq ft/day).

The results of the flotation thickening tests are shown in Figures 11 and 12. Addition of 0.2 kg/m ton (0.4 lbs/ton), of Atlasep IAI polymer helped to produce better flotation thickening results. Solids concentrations of up to 8% could be estimated for the thickened scum. However, due to the dilute nature of the sludge, when a sample was gravity thickened first to about 7% solids and then flotation thickened, solids concentrations of 15 to 19% could be achieved. Optimum recycle rates were between 300 and 400% and mass loading rates of 200-250 kg/sq m/day (40-50 lbs/sq ft/day) could be successfully utilized.

The results of the centrifuge tests for Racine sludge are presented in Table 11. Several samples were tested for centrifugation at various feed solid levels shown in the table. Generally, the tests showed amenability of the

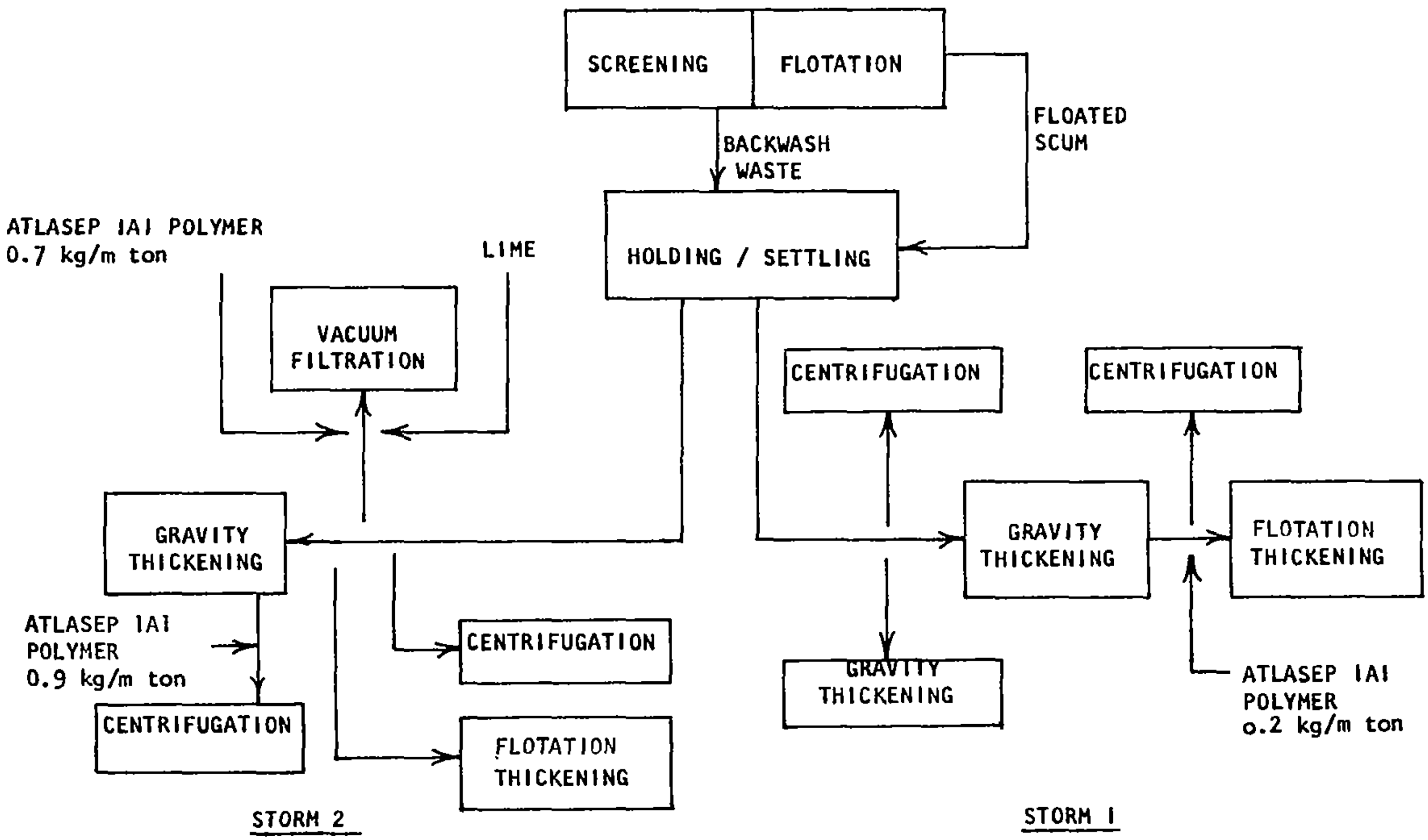

Figure 9. Racine, WI - Bench scale dewatering tests

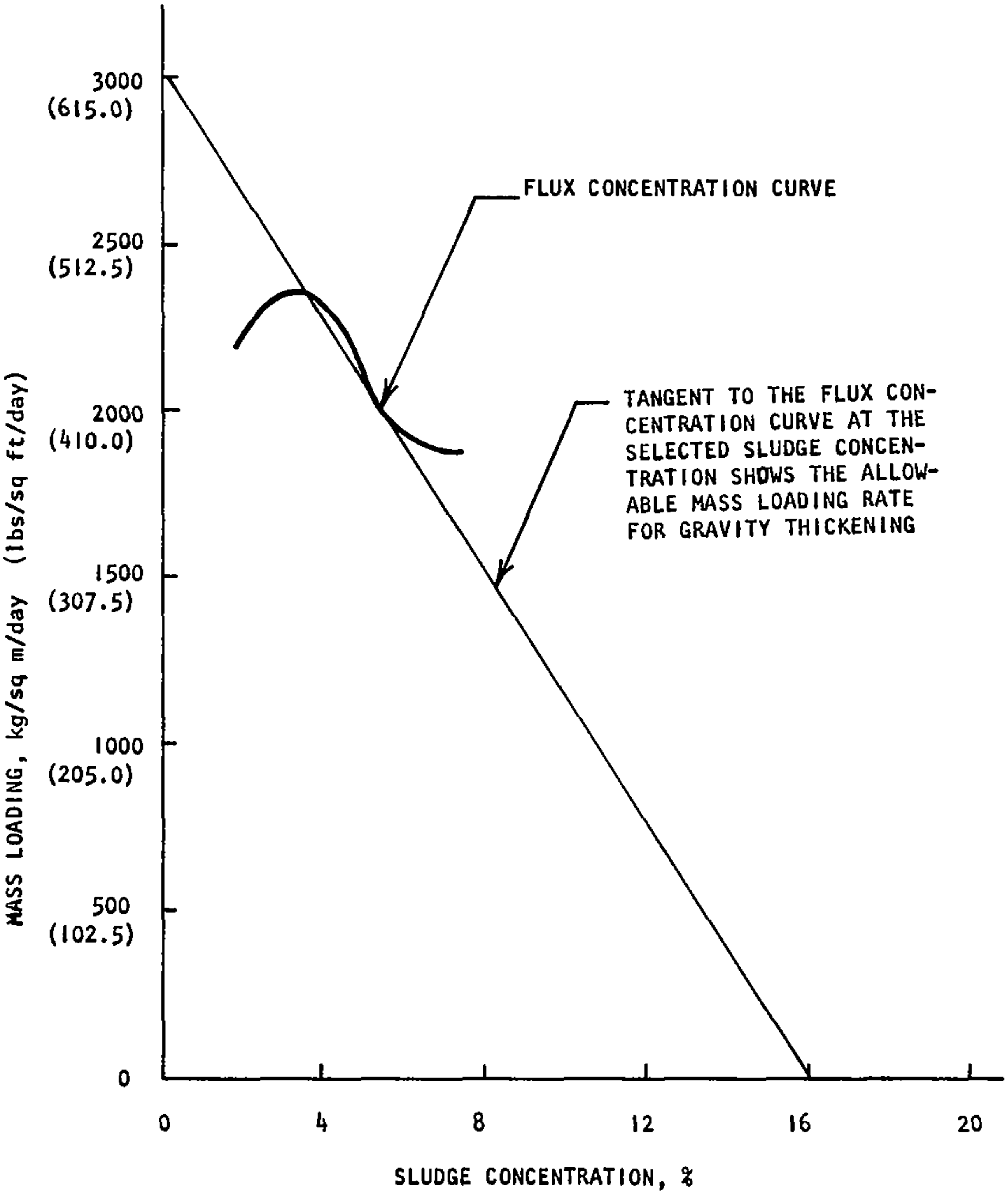

Figure 10. Flux concentration curve for Racine, WI, screening/ dissolved-air flotation sludge - without chemicals

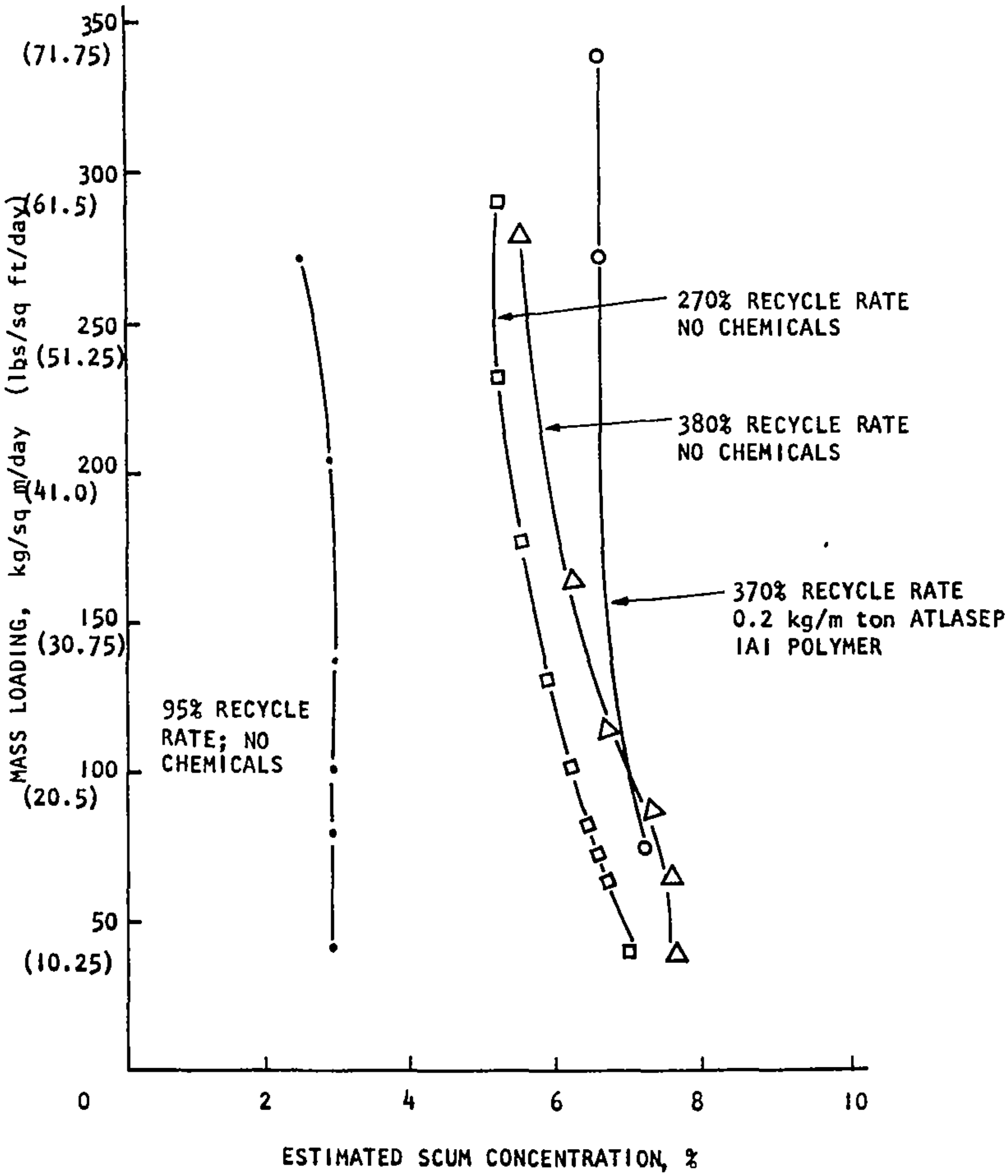

Figure 11. Flotation thickening results for Racine, WI, screening/dissolved-air flotation sludge

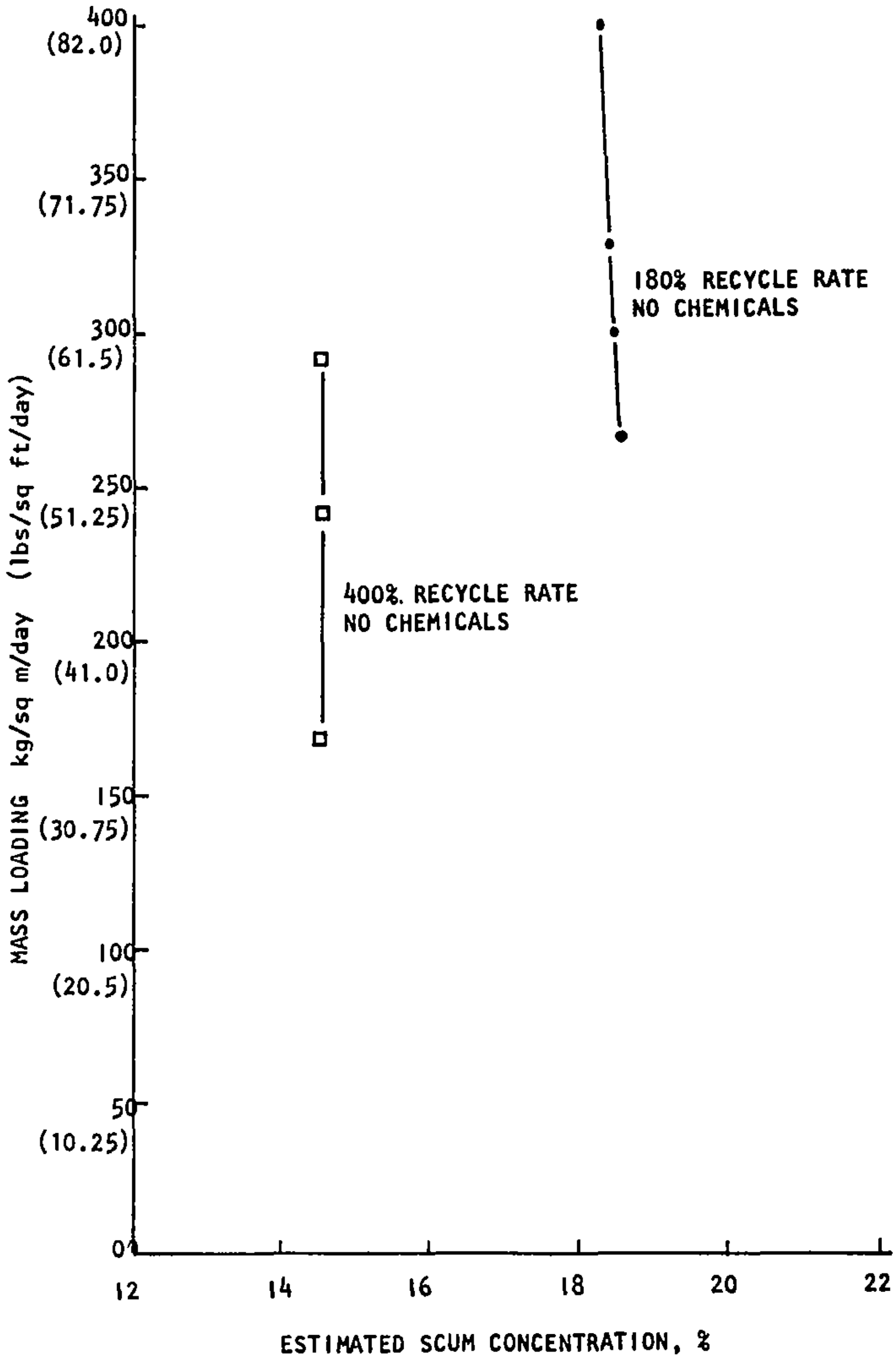

Figure 12. Flotation thickening results for Racine, WI, screening/dissolved-air flotation sludge after pre-gravity thickening to 6.9% solids

Table 11. CENTRIFUGE TESTING RESULTS FOR RACINE, WI, SCREENING/DISSOLVED-AIR FLOTATION SLUDGE

Test No.	Applied G force, "G's"	Spin time, sec	Feed solids, mg/l	Chemical	Dosage, kg/m ton	Centrate solids, mg/l	Centrate volume, ml	Penetration, cm	Sludge depth, cm	Cake solids, %	Penetration, %	Recovery, %	Corrected recovery, %
1	400	60	8,433	none	none	305	71.5	1.3	1.3	17.4	0	96.4	0^a
2	400	90	8,433	none	none	328	72.3	1.2	1.2	22.5	0	96.1	0^a
3	400	120	8,433	none	none	167	72.8	1.2	1.2	28.2	0	98.0	0^a
4	750	60	8,433	none	none	118	73.0	1.0	1.0	31.2	0	98.6	0^a
5	750	90	8,433	none	none	90	72.8	1.15	1.15	28.4	0	98.9	0^a
6	750	120	8,433	none	none	90	71.8	1.1	1.1	19.6	0	98.9	0^a
7	1,000	60	8,433	none	none	104	71.5	1.2	1.2	17.8	0	98.8	0^a
8	1,000	90	8,433	none	none	79	72.0	0.5	1.1	20.9	60	99.1	93
9	1,000	120	8,433	none	none	79	71.8	1.05	1.05	19.6	0	99.1	0^a
10	400	60	75,400	none	none	1,038	52.3	1.05	2.7	24.7	61	98.6	94
11	400	90	75,400	none	none	870	54.8	0.98	2.8	27.8	65	98.8	95
12	400	120	75,400	none	none	850	55.5	1.05	2.7	28.8	61	98.9	94
13	750	60	75,400	none	none	850	56.2	0.80	2.65	29.8	70	98.9	95
14	750	90	75,400	none	none	900	58.0	0.60	2.5	32.9	71	98.8	96
15	750	120	75,400	none	none	755	55.0	0.60	2.75	28.1	78	99.0	97
16	1,000	60	75,400	none	none	1,210	53.8	0.78	2.75	26.4	72	98.4	95
17	1,000	90	75,400	none	none	905	52.0	0.50	2.8	24.4	82	98.8	97
18	1,000	120	75,400	none	none	785	56.5	0.48	2.5	30.3	80	99.0	97
19	400	60	75,400	905-N	0.59	2,710	55.0	0.65	2.75	27.5	76	96.4	94
20	750	60	75,400	905-N	0.59	640	56.0	0.45	2.5	29.6	82	99.2	97
21	1,000	60	75,400	905-N	0.59	425	56.8	0.40	2.55	30.9	84	99.4	98
22	400	120	75,400	905-N	0.59	640	53.5	0.55	2.7	26.1	80	99.2	97
23	750	120	75,400	905-N	0.59	634	54.5	0.4	2.65	27.4	85	99.2	98
24	1,000	120	75,400	905-N	0.59	560	55.0	0.25	2.6	28.1	90	99.2	98
25	400	60	27,200	none	none	6,100	62.0	1.25	2.15	12.8	39	77.6	71
26	750	60	27,200	none	none	3,170	62.0	1.4	2.15	14.2	35	88.3	80
27	1,000	60	27,200	none	none	2,090	61.0	1.05	2.25	13.7	53	99.5	87
28	400	60	27,200	1-A-1	0.98	332	56.0	2.4	2.75	10.6	13	98.8	84
29	750	60	27,200	1-A-1	0.98	317	58.5	1.25	2.35	12.5	47	98.8	92
30	1,000	60	27,200	1-A-1	0.98	285	61.0	0.8	2.25	14.4	64	99.0	95
31	400	120	27,200	none	none	2,200	59.8	1.2	2.3	12.6	48	91.9	85
32	750	120	27,200	none	none	405	59.0	1.3	2.25	12.6	40	98.5	90
33	1,000	120	27,200	none	none	298	60.5	1.3	2.2	13.9	41	98.9	90
34	400	120	27,200	1-A-1	0.98	252	59.0	1.4	2.3	12.7	40	99.1	90
35	750	120	27,200	1-A-1	0.98	222	61.8	1.0	2.2	15.4	55	99.2	93
36	1,000	120	27,200	1-A-1	0.98	206	62.2	0.55	2.05	15.8	73	99.2	96
37	400	60	32,000	1-A-1	0.93	339	49.5	1.35	3.4	9.3	60	98.9	94
38	750	60	32,200	1-A-1	0.93	248	51.5	0.55	3.15	10.2	83	99.2	97
39	1,000	60	32,000	1-A-1	0.93	276	55.0	0.65	2.85	11.9	77	99.1	97
40	400	120	32,000	1-A-1	0.93	313	53.5	0.6	3.0	11.1	80	99.0	97
41	750	120	32,000	1-A-1	0.93	276	55.5	0.5	2.7	12.2	82	99.1	97
42	1,000	120	32,000	1-A-1	0.93	244	56.0	0.5	2.7	12.6	81	99.2	97

a. Denotes poor scrollability of the thickened sludge. See Appendix B for procedure.

sludge to centrifugation. Addition of chemical flocculants aided centrifugation but did not provide very significant improvement in the results. Sludge samples without prior gravity thickening showed high cake solids (20-30%) but the scrollability of this sludge was found to be poor, indicating that a basket type centrifuge would be required for direct sludge centrifugation as opposed to a scroll type centrifuge. However, when the raw sludge was gravity thickened prior to centrifugation, cake solids as high as 30 to 35% could be achieved for a scroll type centrifuge. Optimum solids recoveries were achieved at gravitational forces between 600 and 1,000 G and spin time between 60 and 120 seconds.

Vacuum filtration test results for Racine sludge are presented in Table 12. Buchner Funnel tests indicated that lime at a dosage of 147 kg/m ton (294 lbs/ton) in conjunction with anionic polyelectrolyte, Atlasep IAI, at a dosage of 0.7 kg/m ton (1.4 lbs/ton) provided optimum results for vacuum filtration on sedimented sludge samples with a feed solids concentration of approximately 3%. Optimum cake solids (20 to 25%) with good cake discharge characteristics were observed with either a 4/1 satin multifilament or a 7/1 satin monofilament cloth. Optimum yield rates were between 14 to 18 kg/sq m/hr (2.9 to 3.7 lbs/sq ft/hr) at a submergence of 37.5%. It was also observed that sludge may be free draining and therefore amenable to dewatering via gravity draining. In this regard, one liter of sludge treated with 1.1 kg/m ton (2.2 lbs/ton) IAI was poured on to an open weave filter cloth (1/1 plain weave, saran, monofilament 30x25 threads per inch). After gravity drain of several seconds the cloth was wrapped around the dewatered sludge to form a ball. The sludge ball was then compressed by hand to further dewater the sludge. The filtrate volume was 910 ml. Cake solids were 24.6% and filtrate suspended solids were 405 mg/l. No problem was encountered with discharge from the cloth media. This indicates that a gravity drain-compression or filter press type dewatering may be applicable for such CSO sludges.

Milwaukee, WI (Hawley Road)

A sludge sample of the floated scum without any screen backwash water was obtained from the Hawley Road treatment facility for bench-scale tests. A schematic of the various bench-scale dewatering tests conducted on this sample is shown in Figure 13. Hawley Road is only a small demonstration treatment facility and treats less than 4% of the CSO at its outfall location. Based on published data (20) it is indicated that the flotation scum volumes requiring handling and/or treatment would be approximately 0.7% of the raw CSO volume treated and are comparable to the corresponding residual sludge volumes for Racine and San Francisco flotation scum volumes as discussed in Section V. The flux concentration curves for the gravity thickening tests for this sludge are shown in Figures 14 and 15. The sludge was found to be amenable to gravity thickening and underflow solids concentrations of 8 to 10% could be achieved. Addition of flocculating chemicals aided in the gravity thickening by providing improved mass loading rates (from 200 to 300 kg/day/sq m (40 to 60 lbs/sq ft/day) @10% solids) as shown in the flux curves. Optimum chemical was found to be a cationic polyelectrolyte, Dow C-41, at a dosage of 4 to 5 kg/m ton (8 to 10 lbs/ton).

Table 12. VACUUM FILTRATION TESTING RESULTS FOR RACINE, WI, SCREENING/DISSOLVED-AIR FLOTATION SLUDGE

Feed Solids Concentration - 27,200 mg/l

Chemical dosage, kg/m ton: Al	Chemical dosage, kg/m ton: CaO	Cycle time, min	Pickup time, sec	Dry time, sec	Submergence, %	Yield, $kg/hr/m^2$	Loading, kg/m^2	Cake solids, %	Filtrate solids, mg/l	Filtrate volume, ml	Type of cloth	Cake Discharge characteristics
1.1	0	4	90	100	37.5	--	--	--	--	910	2 X 2 twill multi-filament olefin	No cake
1.1	0	2	45	45	37.5	--	--	--	--	540	2 X 2 twill multi-filament olefin	No cake
1.1	0	1.3	30	30	37.5	--	--	--	--	820	2 X 1 twill saran monofilament	No cake
0	0	2	45	45	37.5	7.09	0.24	20.8	8,550	170	2 X 1 twill saran monofilament	Good thin
0.49	0	2	45	45	37.5	--	--	--	--	345	2 X 1 twill saran monofilament	No cake
0.49	0	2	45	45	37.5	8.38	0.28	18.0	405	250	4 X 1 satin nylon multifilament	Fair
0.49	0	4	90	100	37.5	3.55	0.24	25.0	187	365	4 X 1 satin nylon multifilament	Fair
0.49	110	2	45	45	37.5	18.4	0.61	21.5	74	260	4 X 1 satin nylon multifilament	Excellent
0.49	110	1.3	30	30	37.5	26.7	0.59	18.5	13	220	4 X 1 satin nylon multifilament	Excellent
0.49	110	4	90	100	37.5	16.8	1.12	21.2	6	370	4 X 1 satin nylon multifilament	Excellent
0.74	147	3	65	75	37.5	11.2	0.56	49.0	25	250	4 X 1 satin nylon multifilament	Excellent
0.74	147	4	90	100	37.5	14.2	0.94	23.9	16	325	4 X 1 satin nylon multifilament	Excellent
0.74	147	6	100	130	37.5	14.8	1.48	21.4	11	380	Satin polypropylene	Excellent
0.74	147	3	65	75	37.5	17.0	0.85	23.2	1,400	460	Satin polypropylene	Excellent
0.74	147	4	90	100	37.5	21.0	1.40	21.6	2,090	480	Satin polypropylene	No cake
1.1	0	3	90	100	37.5							

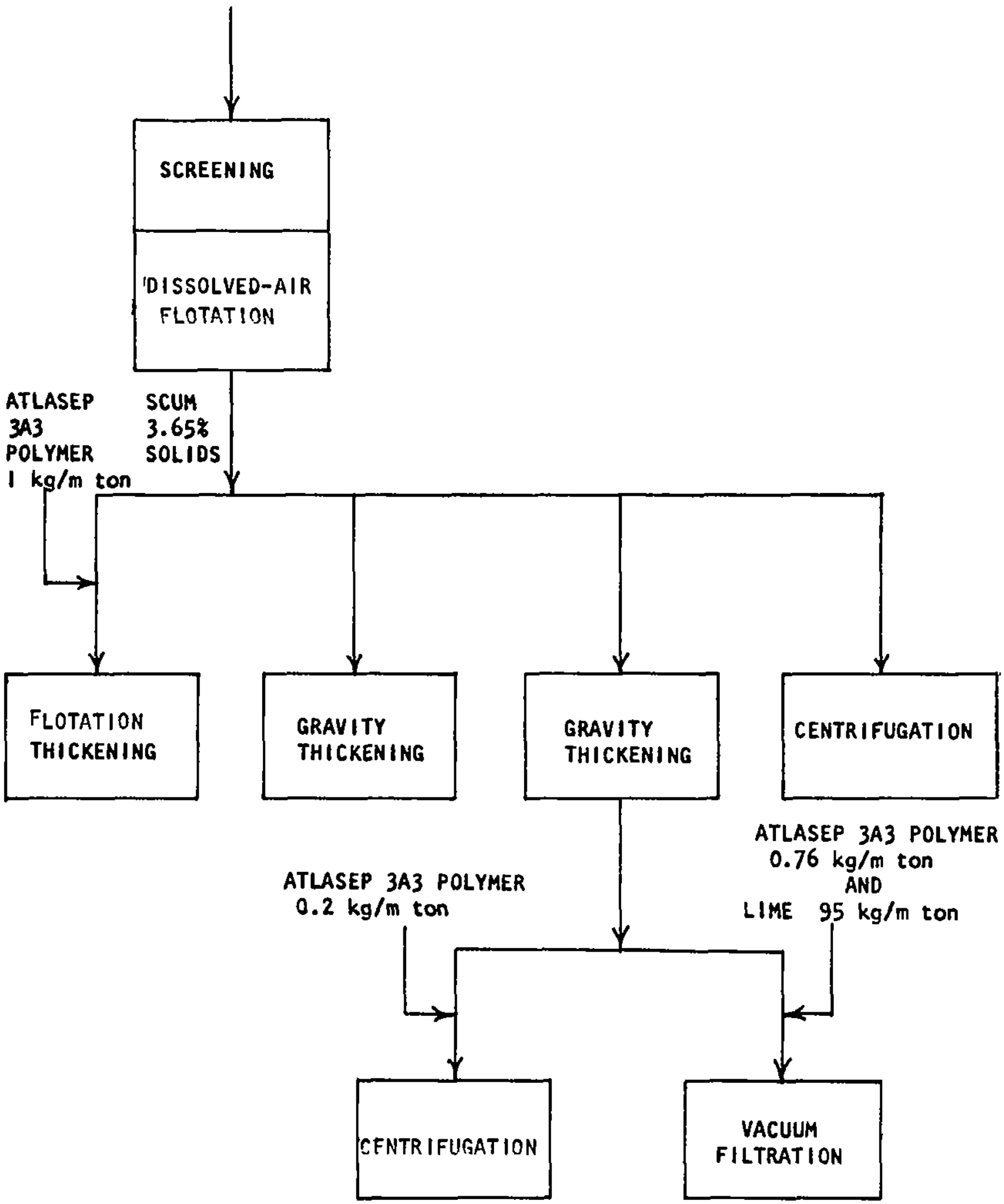

Figure 13. Milwaukee, WI (Hawley Road) - bench scale dewatering tests

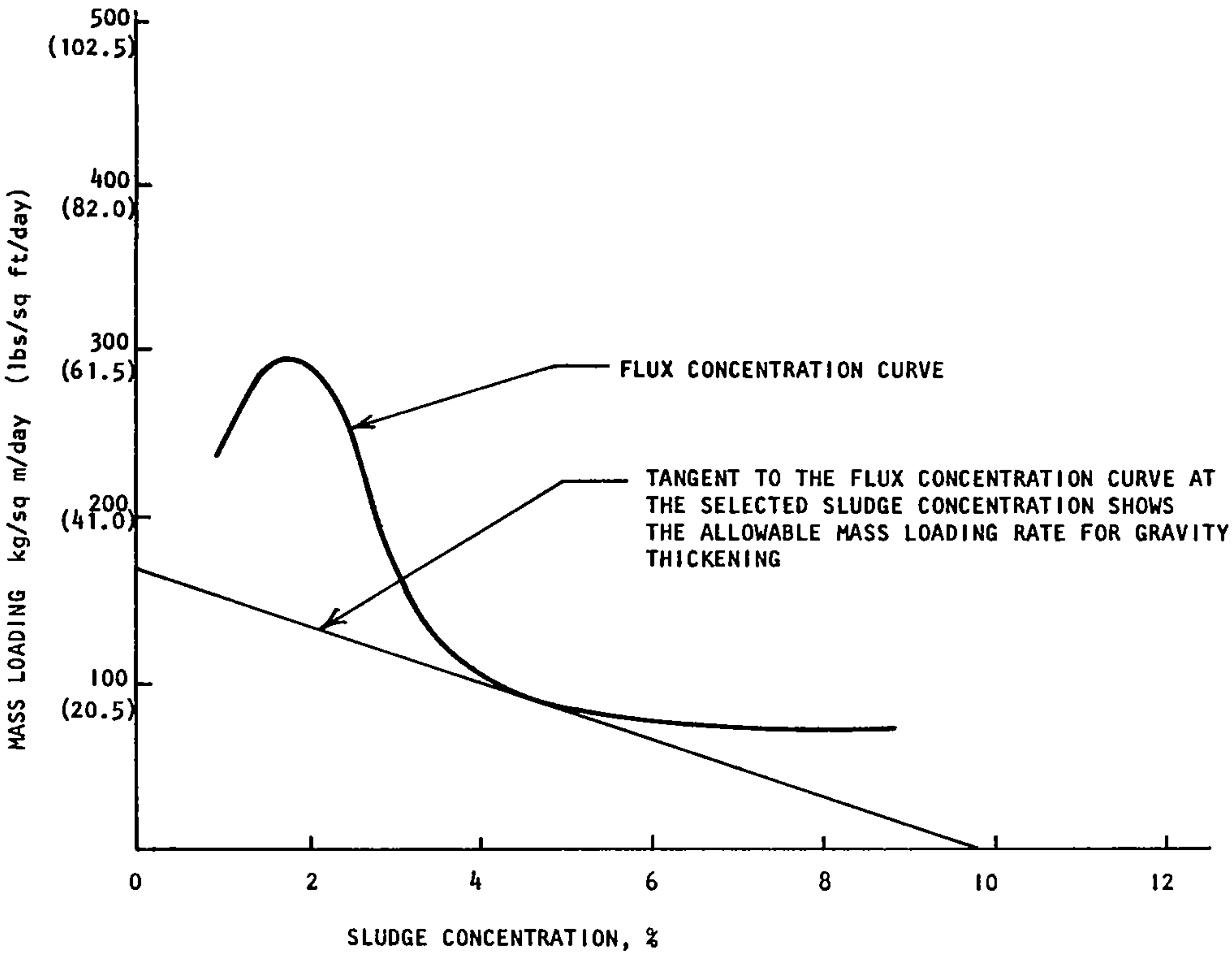

Figure 14. Flux concentration curve for Milwaukee, WI (Hawley Road), dissolved-air flotation sludge, without chemicals

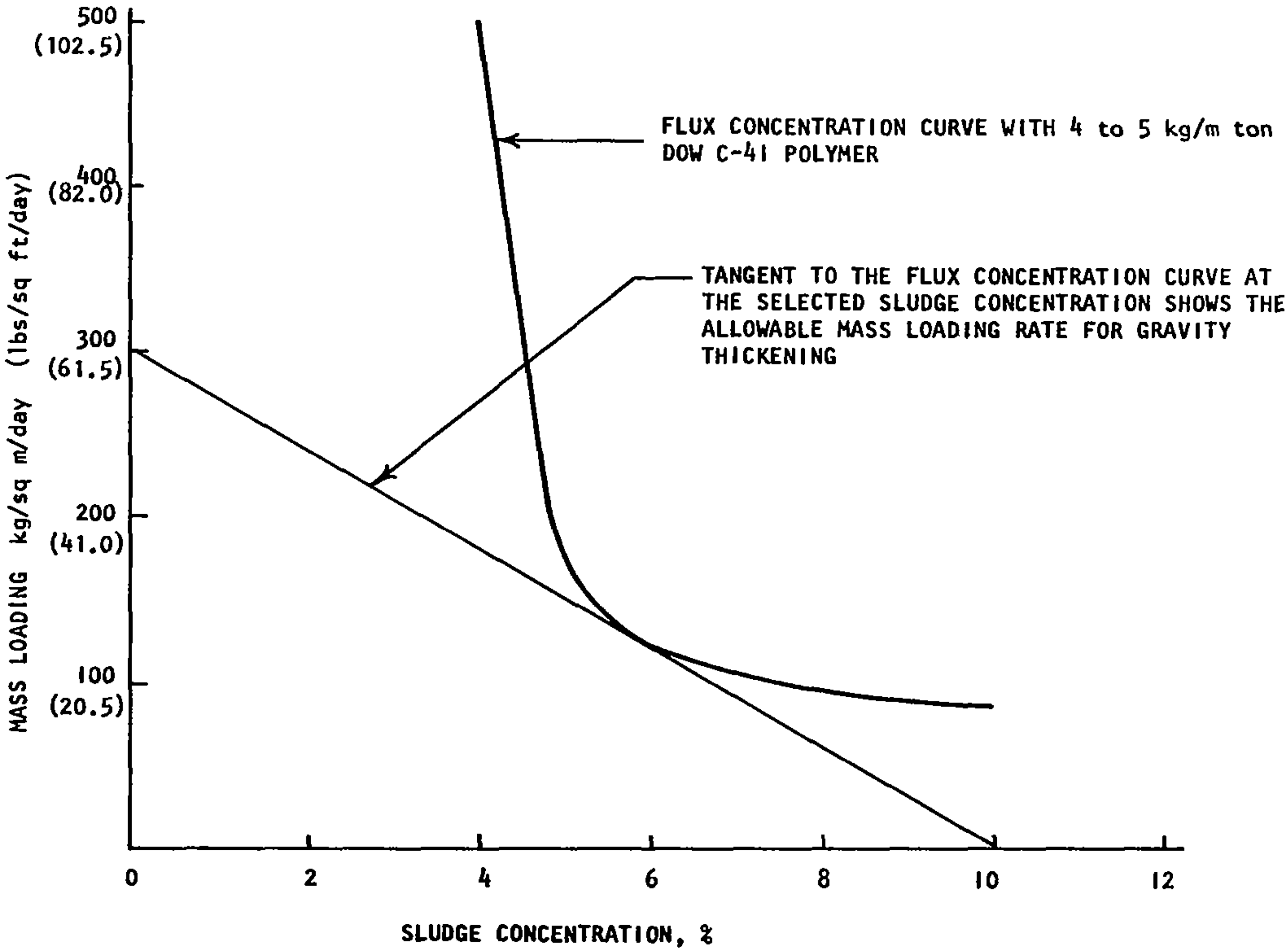

Figure 15. Flux concentration curve for Milwaukee, WI, (Hawley Road) dissolved-air flotation sludge with chemicals

The results of flotation thickening tests are shown in Figure 16. Without the aid of any chemicals, scum concentrations of up to 15% could be expected at a solids loading rate of approximately 75 kg/sq m/day (15 lbs/sq ft/day). However, use of an anionic polyelectrolyte, Atlasep 3A3, provided a scum concentration of 10-11% at significantly higher loading rates of the order of 250-350 kg/sq m/day (50-70 lbs/sq ft/day). Optimum recycle rates ranged between 350 and 400%.

Centrifugation test results are shown in Table 13. Again, prior gravity thickening and chemical addition (0.2 kg/m ton, Atlasep 3A3) helped to provide improved cake solids. Raw scum yielded a cake solids concentration in the range of 19 to 23% while chemically treated and sedimented sludge (feed concentration 9-10% solids) yielded cake solids of approximately 22 to 30% upon centrifugation. Optimum solids recoveries were achieved at gravitational forces between 700 and 1,000 G and spin time between 60 and 120 seconds.

Vacuum filtration tests on this sludge were conducted on gravity thickened samples having a feed solids concentration of 10.3%. The test results are shown in Table 14. Buchner Funnel tests showed that a chemical combination of lime (95 kg/m ton) and Atlasep 3A3 (0.8 kg/m ton) provided optimum test results. Cake solids of up to 30% were achieved under optimum chemical conditions. Optimum yield rates of 50 kg/sq m/hr (10 lbs/sq ft/hr) were achieved at 37.5% submergence.

San Francisco, CA

A treatment schematic of the various bench scale tests conducted on the San Francisco sludge sample is shown in Figure 17. The grab sample obtained for bench tests had a suspended solids concentration of 2.25% as compared to the flotation scum sample for Hawley Road at 3.65% solids. The flux concentration curve for the gravity thickening tests for this sludge is shown in Figure 18. The results showed generally poor settling characteristics. Chemical coagulants were necessary for any meaningful gravity thickening results. Even with the aid of chemical coagulants (up to 12 kg/m ton of Atlasep 105C, a cationic polyelectrolyte), the sludge was thickeded only to a level of 2 to 3% solids at low mass loading rates of 50 to 70 kg/sq m/day (10-14 lbs/sq ft/day). At significantly reduced loading rates of the order of 10 to 20 kg/sq m/day (2 or 4 lbs/sq ft/day); thickening up to 4% solids may be possible. It was indicated that such poor performance for gravity thickening may be due to the alum treatment of CSO utilized at this treatment facility.

The results of flotation thickening tests are shown in Figures 19 and 20. Scum concentrations of up to 5 to 6% solid could be achieved at mass loading rates between 50 to 100 kg/sq m/day (10-20 lbs/sq ft/day) and recycle rates between 350 and 450%. With the aid of Atlasep 105C (0.4 to 0.5 kg/m ton dosage), maximum concentration of only 7.5% solids was possible at similar mass loadings and recycle rates. (It should be noted that the Atlasep 105C polymer used here has since been discontinued for production by the manufacturer but any equivalent polymer should provide comparable performance). Centrifuge test data for the

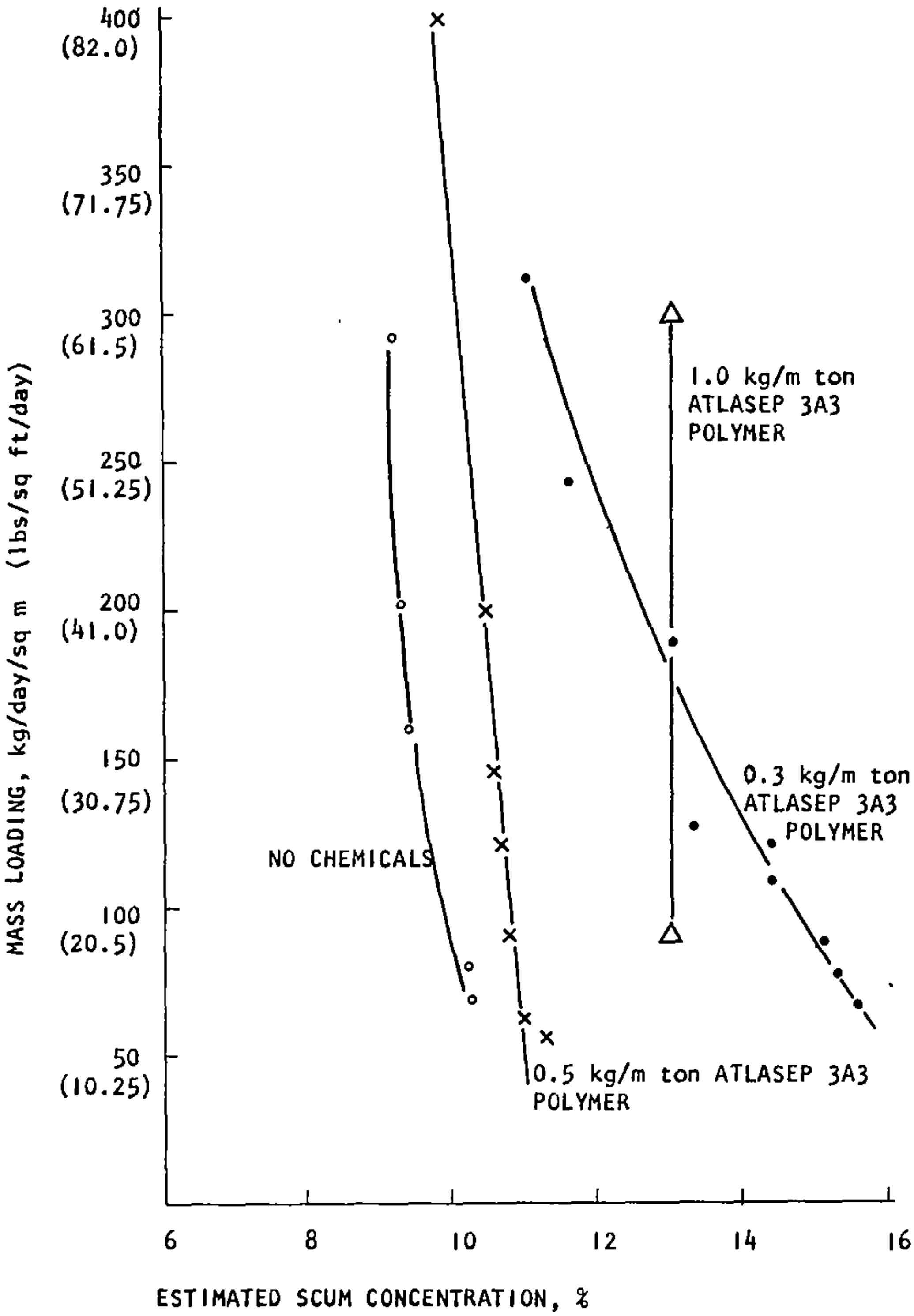

Figure 16. Flotation thickening results for Milwaukee, WI, Hawley Road., dissolved-air flotation sludge (all tests at 390% recycle rate for thickening)

Table 13. CENTRIFUGE TESTING RESULTS FOR MILWAUKEE, WI, HAWLEY ROAD, DISSOLVED-AIR FLOTATION SLUDGE

Test No.	Applied G force, "G's"	Spin time, sec	Feed solids, mg/l	Chemical	Dosage, kg/m ton	Centrate solids, mg/l	Centrate volume, ml	Penetration, cm	Sludge depth, cm	Cake solids, %	Penetration, %	Recovery, %	Corrected recovery, %
1	400	30	36,540	none	none	5,475	59.5	2.1	2.1	15.6	0	85.0	0.0[a]
2	400	60	36,540	none	none	300	59.3	2.1	2.1	17.4	0	99.4	0.0[a]
3	400	90	36,540	none	none	210	62.3	1.6	1.9	21.4	14	99.5	81.7
4	400	120	36,540	none	none	208	62.9	1.4	2.1	21.1	34	99.5	89.6
5	700	30	36,540	none	none	776	58.8	2.2	2.3	16.9	4	97.8	70.9
6	700	60	36,540	none	none	96	61.0	1.4	2.4	19.6	41	99.7	91.2
7	700	90	36,540	none	none	171	60.8	1.3	1.9	19.2	34	99.6	89.4
8	700	120	36,540	none	none	161	62.5	1.1	1.7	21.9	31	99.6	88.6
9	1,000	30	36,540	none	none	204	58.3	2.0	2.3	16.9	14	99.5	81.7
10	1,000	60	36,540	none	none	142	62.0	1.3	1.9	21.1	31	99.7	88.7
11	1,000	90	36,540	none	none	153	63.0	1.1	2.0	22.8	44	99.7	91.3
12	1,000	120	36,540	none	none	134	63.3	1.0	1.7	23.4	45	99.7	92.0
13	700	30	99,200	Atlasep 3A3	0.20	865	42.0	3.2	3.9	22.4	18	99.1	83.5
14	700	75	99,200	Atlasep 3A3	0.20	332	48.0	1.7	3.3	27.5	54	99.7	93.8
15	700	120	99,200	Atlasep 3A3	0.20	298	50.5	1.3	3.3	30.3	61	99.7	94.9
16	1,000	30	99,200	Atlasep 3A3	0.20	1,770	45.0	2.8	3.9	24.5	30	98.2	87.1
17	1,000	75	99,2000	Atlasep 3A3	0.20	424	48.0	1.8	3.4	27.5	46	99.6	92.2
18	1,000	120	99,2000	Atlasep 3A3	0.20	465	50.0	1.6	3.2	29.7	50	99.5	92.8

a. Denotes poor scrollability of thickened sludge. See Appendix B for procedure.

Table 14. VACUUM FILTRATION TESTING RESULTS MILWAUKEE, WI, HAWLEY ROAD, DISSOLVED-AIR FLOTATION SLUDGE

Feed solids concentration 10.3%

Chemical dosage, kg/m ton 3A3	Chemical dosage, kg/m ton CaO	Cycle time, min	Pickup time, sec	Dry time, sec	Submergence, %	Yield, kg/hr/m^2	Loading, kg/m^2	Cake solids, %	Filtrate solids, mg/l	Filtrate volume, ml	Type of cloth	Cake Discharge characteristics
0.76	95	5	75	150	25	37.1	3.08	35.7	232	235	2x2 twill olefin multifilament	Excellent
0.76	95	4	90	100	37.5	50.8	3.38	30.4	463	197	2x2 twill olefin multifilament	Excellent
0.36	95	4	90	100	37.5	50.2	3.34	31.1	3,591	200	2x1 plain polypropylene monofilament	Excellent
0.38	95	4	90	100	37.5	49.9	3.33	31.7	--	--	2x2 twill olefin multifilament	Excellent

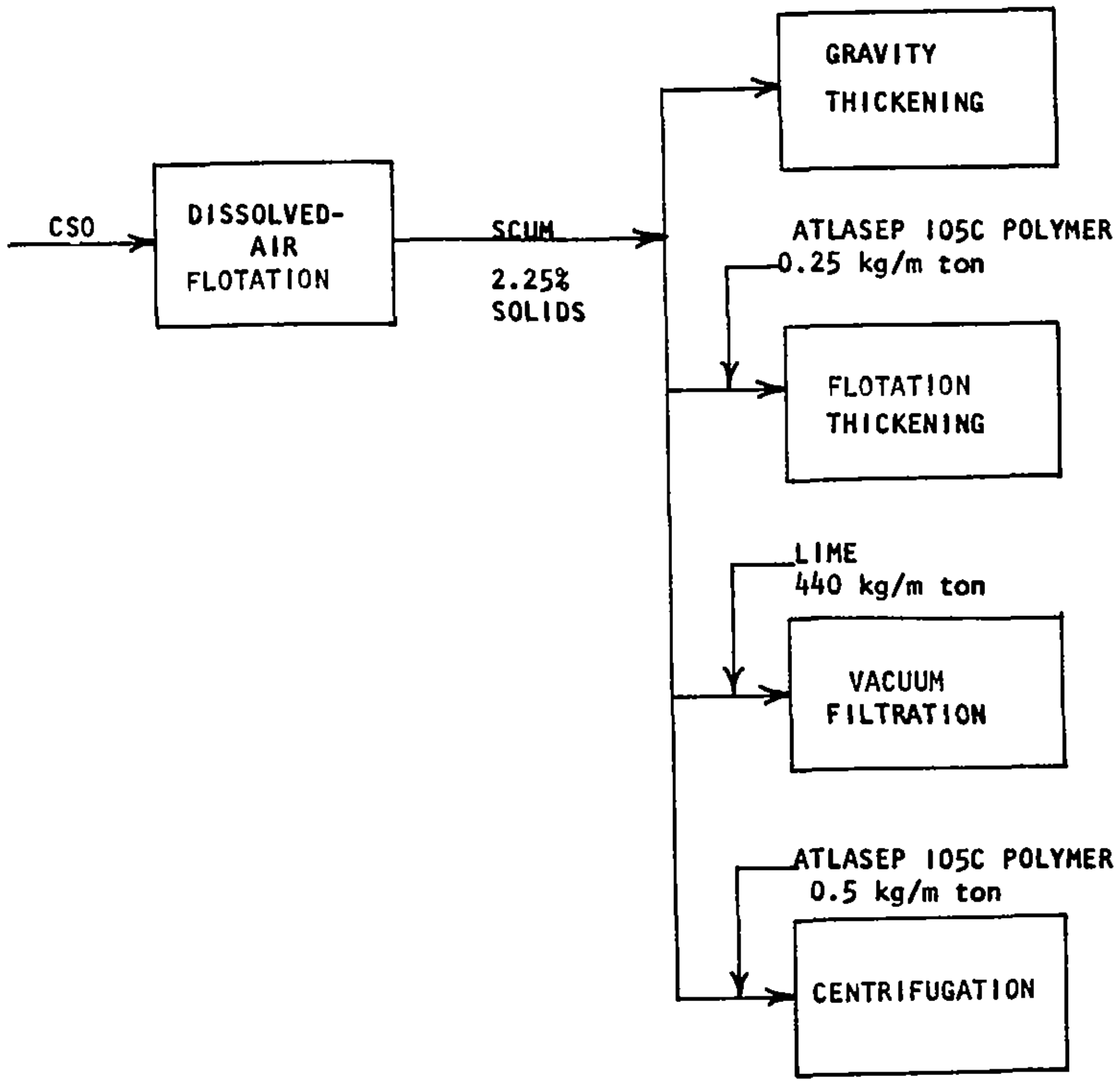

Figure 17. San Francisco, CA, - bench scale dewatering tests

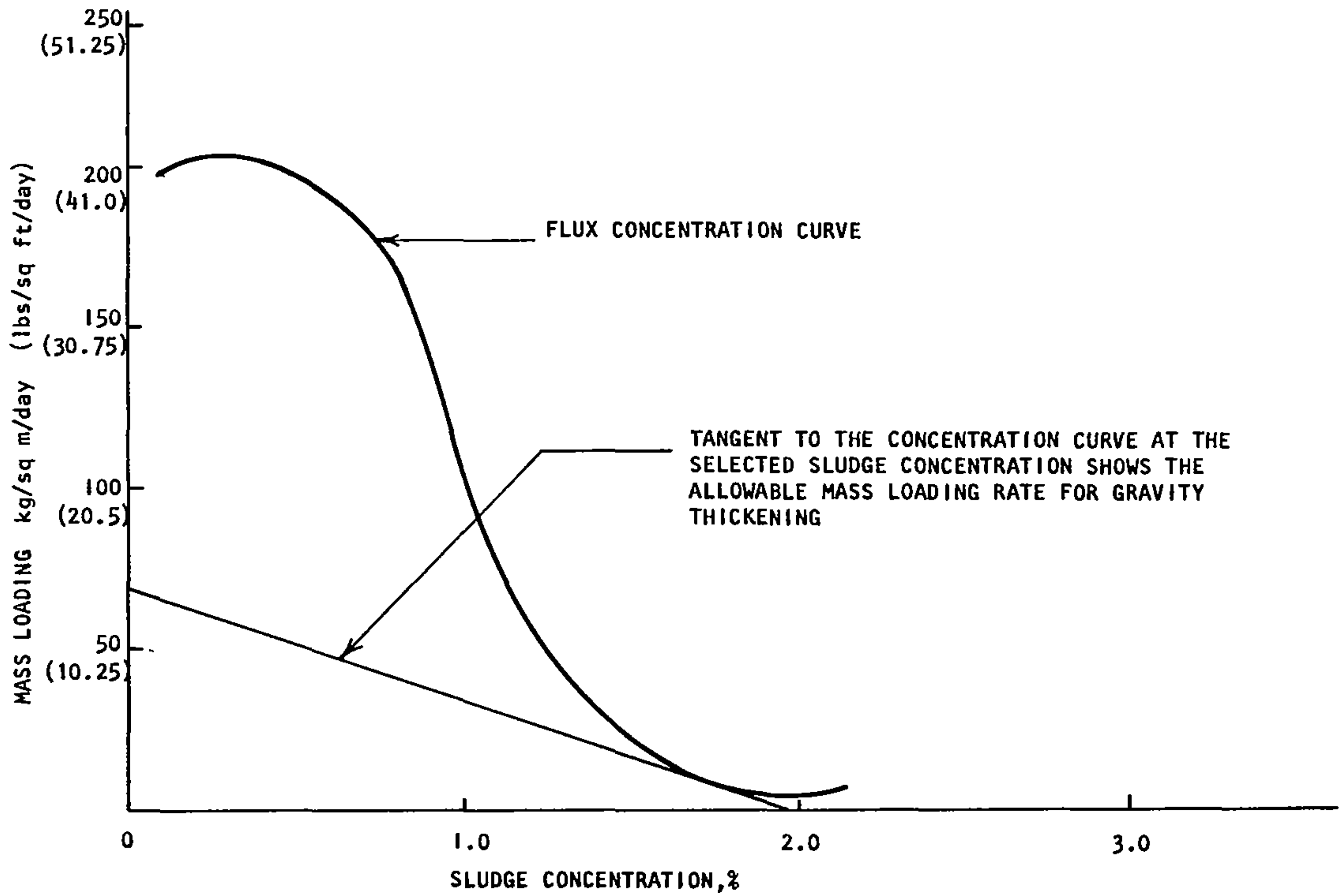

Figure 18. Flux concentration curve for San Francisco, CA, dissolved-air flotation sludge (with chemicals)

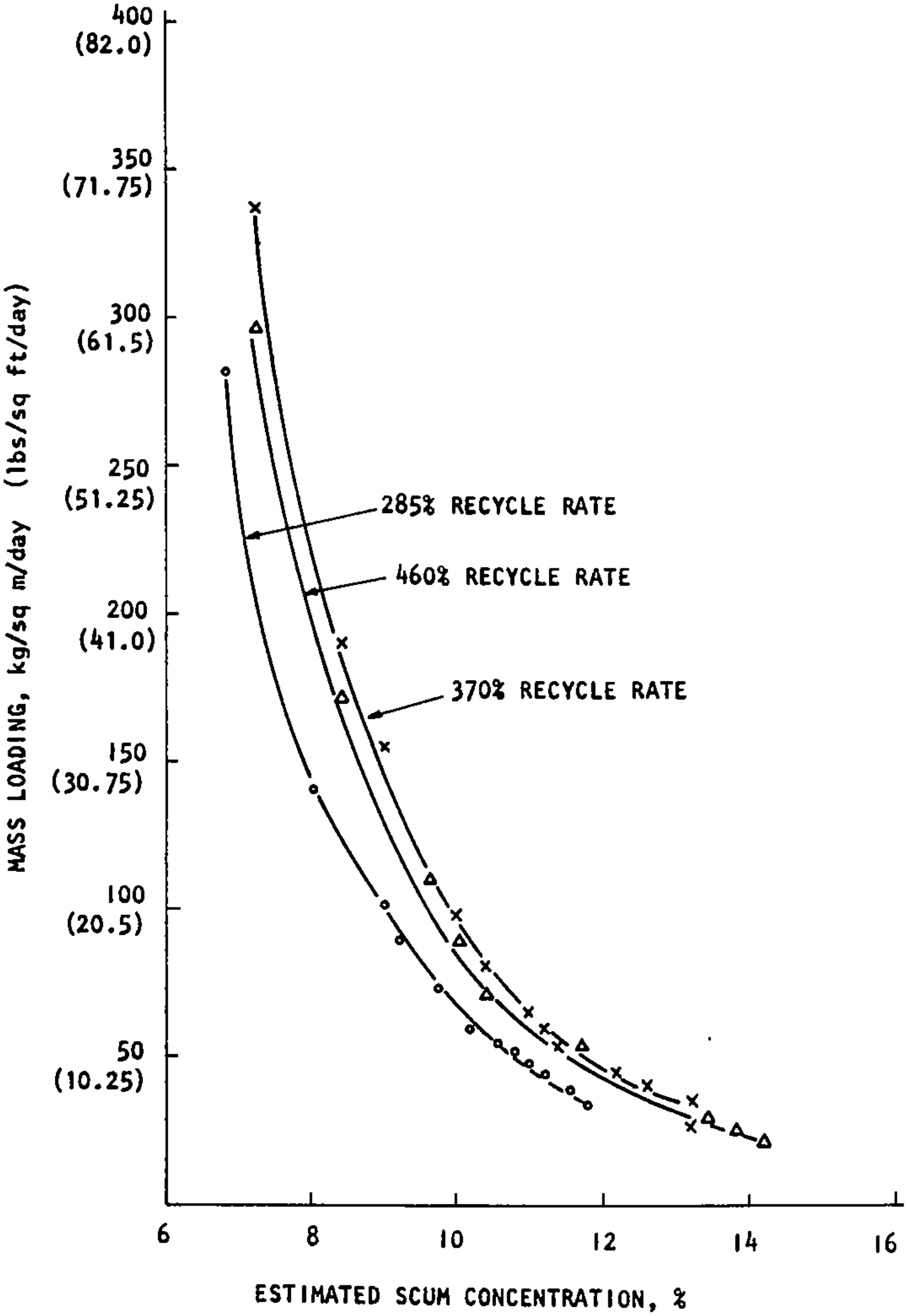

Figure 19. Flotation thickening results for San Francisco, CA dissolved-air flotation sludge - without chemicals

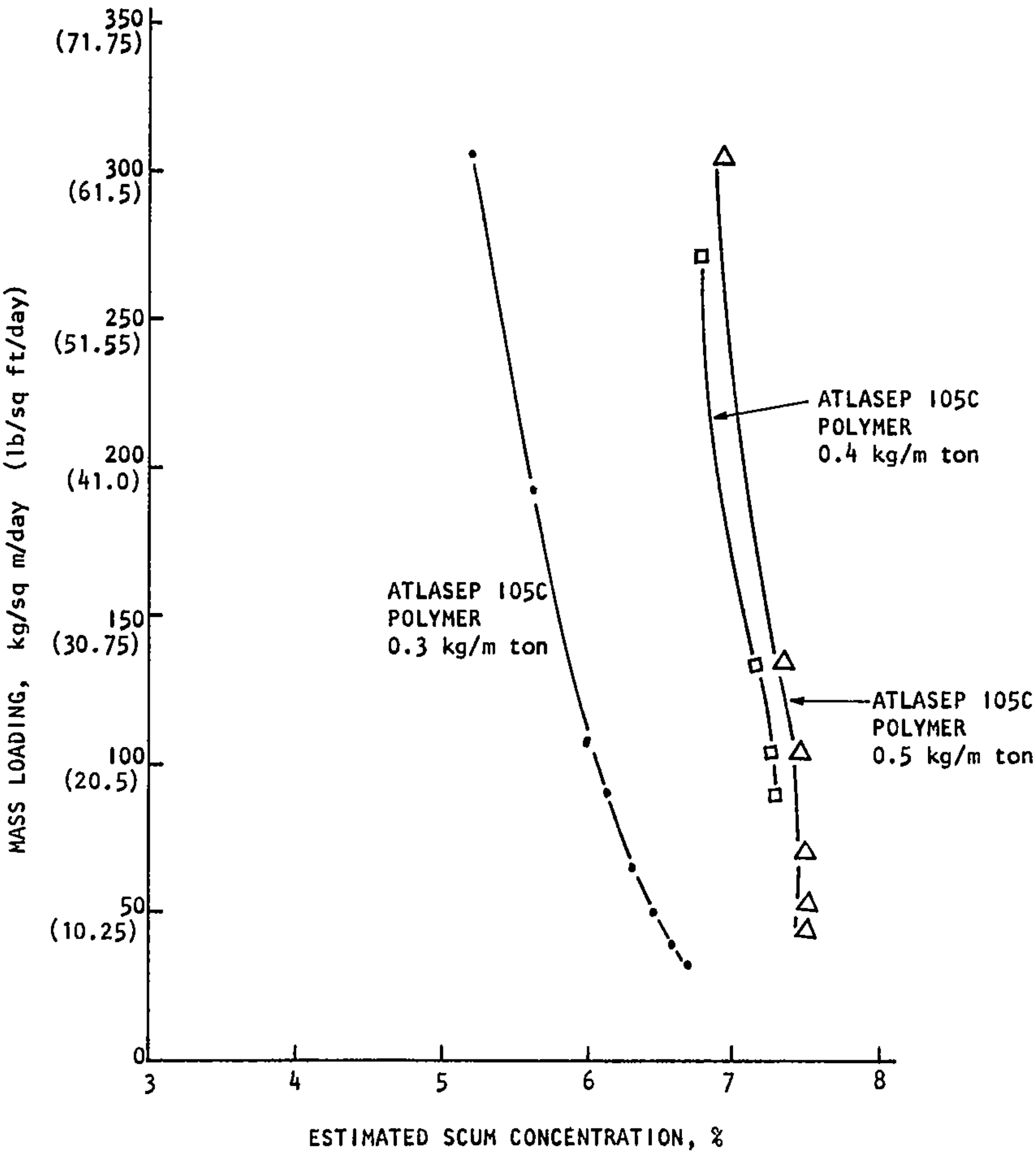

Figure 20. Flotation thickening results for San Francisco, CA dissolved-air flotation sludge - with chemicals (all tests at 370% recycle rate for thickening)

San Francisco sample is presented in Table 15. Without chemical treatment, the sludge showed poor scrollability characteristics and could be concentrated only to about 7-8% solids. However, concentrations up to 11% solids were achieved when chemical treatment with Atlasep 105C (0.5 kg/m ton) was utilized. It was indicated that the chemically treated sludge could be treated with both the scroll and basket type centrifuges. Marked improvement in the centrate clarity was also achieved with chemical clarification.

The results of the vacuum filtration tests are shown in Table 16. Buchner Funnel tests indicated that best filtration results were obtained with large dosages of lime (350 to 450 kg/m ton) instead of the cationic polyelectrolyte, Atlasep 105C that had shown optimum results for other dewatering techniques. A 3 x 1 twill weave filter media provided the best cake discharge characteristics with lime treatment. The loading and yield rates shown in Table 16 are based on dry weight of sludge solids. Cake solids of approximately 18% for a yield of 15 to 20 kg/sq m/hr (3 to 4 lbs/sq ft/hr) were achieved for the thickened sludge.

Treatment Costs for Physical/Chemical CSO Sludges

A summary of the estimated area and cost requirements of various dewatering techniques under optimum treatment conditions for Physical/Chemical CSO sludges is shown in Table 17. As mentioned earlier for storage treatment the total costs shown include the amortization of capital costs and the hauling cost of the ultimate treatment residuals from the site along with other operating costs such as labor, chemical, maintenance, power, etc. Details of these cost estimates and the assumptions made to arrive at them are presented in Appendix C. It is evident that generally centrifugation alone or in combination with gravity thickening are the optimum dewatering steps based on performance, area and cost requirements. For Racine and San Francisco, basket type centrifuges were considered for cost calculations based on the results of the feasibility tests. It is interesting to note that the total cost of gravity or flotation thickening is significantly more than centrifugation or vacuum filtration even when the latter are in combination with the former. The reason for such a difference stems from the hauling cost of the ultimate treatment residuals, which are significantly larger in volume for gravity thickening and flotation thickening compared to the residual volumes after centrifugation or vacuum filtration. For San Francisco, the cost results of centrifugation and vacuum filtration are close; while vacuum filtration edges out centrifugation in thickened solids performance. This may be due to the nature of the raw sludge because of the use of alum treatment at San Francisco, compared to ferric chloride treatment at Racine and Milwaukee (Hawley Road).

C. BIOLOGICAL TREATMENT

Sludge samples from two sites using biological treatment were procured. Both these sites are operated during wet-weather as well as dry-weather. A wet-weather sludge sample was procured from Kenosha, WI where the contact stabilization activated sludge process is utilized. Four sludge samples were procured

Table 15. CENTRIFUGE TESTING RESULTS FOR SAN FRANCISCO, CA, DISSOLVED-AIR FLOTATION SLUDGE

No.	Applied G force, "G's"	Spin time, sec	Feed solids, %	Chemical	Dosage, kg/m ton	Centrate solids, mg/l	Centrate volume, ml	Penetration, cm	Sludge depth, cm	Cake solids, %	Penetration, %	Recovery, %	Corrected recovery, %
1	400	30	2.25	none	none	--	--	--	--	--	0	--	0[a]
6	600	60	2.25	none	none	6,925	59.5	3	3	8.2	0	69.2	0[a]
7	800	60	2.25	none	none	4,825	58.0	2.8	2.8	8.3	0	78.5	0[a]
8	1,000	60	2.25	none	none	3,260	57.8	2.7	2.7	8.3	0	85.7	0[a]
10	600	90	2.25	none	none	3,690	55.5	3.0	3.0	7.6	0	83.6	0[a]
11	800	90	2.25	none	none	2,260	56.0	2.8	2.8	8.2	0	89.9	0[a]
12	1,000	90	2.25	none	none	1,500	56.5	2.68	2.68	8.7	0	93.3	0[a]
13	400	120	2.25	none	none	1,460	56.5	2.73	2.73	8.7	0	93.7	0[a]
14	600	120	2.25	none	none	2,275	55.0	2.73	2.73	7.8	0	89.8	0[a]
15	800	120	2.25	none	none	1,350	56.0	2.63	2.63	8.5	0	94.0	0[a]
16	1,000	120	2.25	none	none	1,025	57.5	2.6	2.6	9.3	0	95.4	0[a]
17	400	30	2.25	105C	0.53	89	53.0	3.05	3.05	7.6	0	99.6	0[a]
18	700	30	2.25	105C	0.53	51	54.8	2.85	2.85	8.3	0	99.7	0[a]
19	1,000	30	2.25	105C	0.53	72	55.8	2.63	2.63	8.8	0	99.6	0[a]
20	400	60	2.25	105C	0.53	67	55.0	2.8	2.8	8.4	0	99.7	0[a]
21	700	60	2.25	105C	0.53	98	58.2	1.3	2.53	10.0	48	99.5	92.4
22	1,000	60	2.25	105C	0.53	66	58.3	1.3	2.38	10.1	43	99.7	91.6
23	400	90	2.25	105C	0.52	80	55.2	2.75	2.75	8.5	0	99.6	0[a]
24	700	90	2.25	105C	0.52	73	58.8	0.85	2.5	10.4	64	99.6	95.2
25	1,000	90	2.25	105C	0.53	56	59.2	1.5	2.35	10.6	35	99.7	89.8
26	400	120	2.25	105C	0.53	82	59.0	1.1	2.63	10.5	58	99.6	94.3
27	700	120	2.25	105C	0.53	132	59.8	0.8	2.53	11.0	68	99.4	95.6
28	1,000	120	2.25	105C	0.53	33	59.8	1.2	2.35	11.1	48	99.8	92.7

a. Denotes poor scrollability of thickened sludge. See Appendix B for procedure.

Table 16. VACUUM FILTRATION TESTING RESULTS FOR SAN FRANCISCO, CA, DISSOLVED-AIR FLOTATION SLUDGE

Feed solids concentration: 2.25%

Chemical	Dosage, kg/m ton	Cycle time, min	Pickup time, sec	Dry time, sec	Submergence, %	Yield, kg/hr/m^2	Loading, kg/m^2	Cake solids, %	Filtrate solids, mg/l	Filtrate volume, mg/l	Type of cloth	Cake Discharge characteristics
105-C	0.66	5	75	150	25	--	--	No Cake	147	580	3X1 twill	Poor
105-C	0.66	6	175	195	37.5	--	--	23.3	62	530	3X1 twill	Poor
CaO	356	7.8	170	190	37.5	--	--	24.7	77	255	3X1 twill	Good
CaO	444	8	170	190	37.5	11.4	1.48	18.2	123	680	3X1 twill	Very Good
CaO	444	5	110	122	37.5	14.7	1.23	18.0	134	520	3X1 twill	Very Good
CaO	444	3	65	73	37.5	19.3	0.96	18.1	110	405	3X1 twill	Very Good
CaO	444	2	44	48	37.5	21	0.70	18.4	146	300	3X1 twill	Very Good
CaO	444	3	44	92	25	13.5	0.67	18.7	108	310	3Y1 twill	Very Good

Table 17. SUMMARY OF AREA AND COST REQUIREMENTS FOR PHYSICAL/CHEMICAL SLUDGES UNDER OPTIMUM TREATMENT CONDITIONS

Site	Racine				Hawley Road				San Francisco			
	Sludge solids, %	Area sq ft	Area (sq m)	Total annual cost[a], $/yr	Sludge solids, %	Area sq ft	Area (sq m)	Total annual cost[a], $/yr	Sludge solids, %	Area sq ft	Area (sq m)	Total annual cost[a], $/yr
Gravity thickening	10	172	(16)	54,800	10	312	(29)	71,500	4	1,959	(182)	45,000
Flotation thickening	13[b]	1,400	(130)	63,800	13	797	(74)	69,200	6	172	(16)	40,500
Centrifugation	20	194	(18)	56,900	23	21.5	(2)	39,800	11	32	(3)	24,600
	33[b]	205	(19)	32,400	30[b]	345	(32)	38,100				
Vacuum filtration	23[b]	323	(30)	44,100	36[b]	452	(42)	41,300	18	129	(12)	23,900

a. Capital costs amortized for 20 year equipment life and 10% interest rate. For details of cost estimates, See Appendix C.

b. These tests conducted on gravity thickened sludge.

All costs based on December, 1974 prices.

from the primary and secondary clarifiers at New Providence, NJ where trickling filtration treatment is utilized during both the wet and dry-weather treatment periods.

Kenosha, WI

A treatment schematic of the bench scale dewatering techniques investigated at Kenosha is shown in Figure 21. The average quantity of sludge requiring handling and/or treatment on a per storm basis was estimated to be 464 cu m (122,600 gal.) at a suspended solids concentration of 0.8 to 1.0% solids. These values are based on published data (12) and analytical results obtained during this study. The flux concentration curves for the gravity thickening tests are shown in Figures 22 and 23. These curves represent the test data without chemicals and with chemicals respectively. As can be seen from these curves, this sludge showed poor amenability to gravity thickening both with and without chemical aids. Sludge concentrations of less than 2% solids could be achieved at low solids loadings 10-20 kg/sq m/day (2-4 lbs/sq ft/day). Such performance of a biological sludge is similar to gravity thickening performance of conventional dry-weather biological sludges.

The flotation thickening test results are shown in Figures 24 and 25. Optimum recycle rate was found to be approximately 200%. Chemical dosage tests were conducted using Dow C-31, a cationic polyelectrolyte and Atlasep 3A3, an anionic polyelectrolyte based on chemical screening tests. The cationic polymer, C-31, produced optimum results and concentrations of 4 to 5% solids could be achieved at mass loading rates of 50-100 kg/sq m/day (10-20 lbs/sq ft/day).

Data on the centrifugation tests for the Kenosha sludge sample is shown in Table 18. Bench test procedure for a scroll type centrifuge indicated poor scrollability as evidenced by the zero resistance to penetration of the centrifuged sludge in all tests. Chemical aids did not provide any improvement in test results both in terms of cake solids, centrate clarity or scrollability of the centrifuged sludge. Therefore, it was concluded that scroll type centrifuge would not be applicable to the biological sludge at Kenosha. However, a basket type centrifuge is expected to produce positive results as evidenced by the cake solids up to 9% for centrifuged sludge (test no. 8) under optimum test conditions of 1000G and 120 seconds detention time. A combination of flotation thickening and centrifugation did not provide any improvement in the test results for a scroll type centrifuge.

The results of vacuum filtration tests are shown in Table 19. Because of the dilute nature of the raw sludge, all filtration tests were conducted after flotation thickening of the raw sludge to a level of 3.1% solids. Chemical dosage screening tests on a Buchner Funnel showed that a chemical combination of 160 kg/m ton (220 lbs/ton) ferric chloride and 128 kg/m ton/ (256 lbs/ton) lime provided optimum filtration results of the various filter media investigated, best cake discharge characteristics were obtained with the 4/1 satin nylon multifilament cloth. Cake solids of up to 15% for a yield of approximately 18 kg/sq m/hr (3.6 lbs/sq ft/hr) were achieved under optimum test conditions.

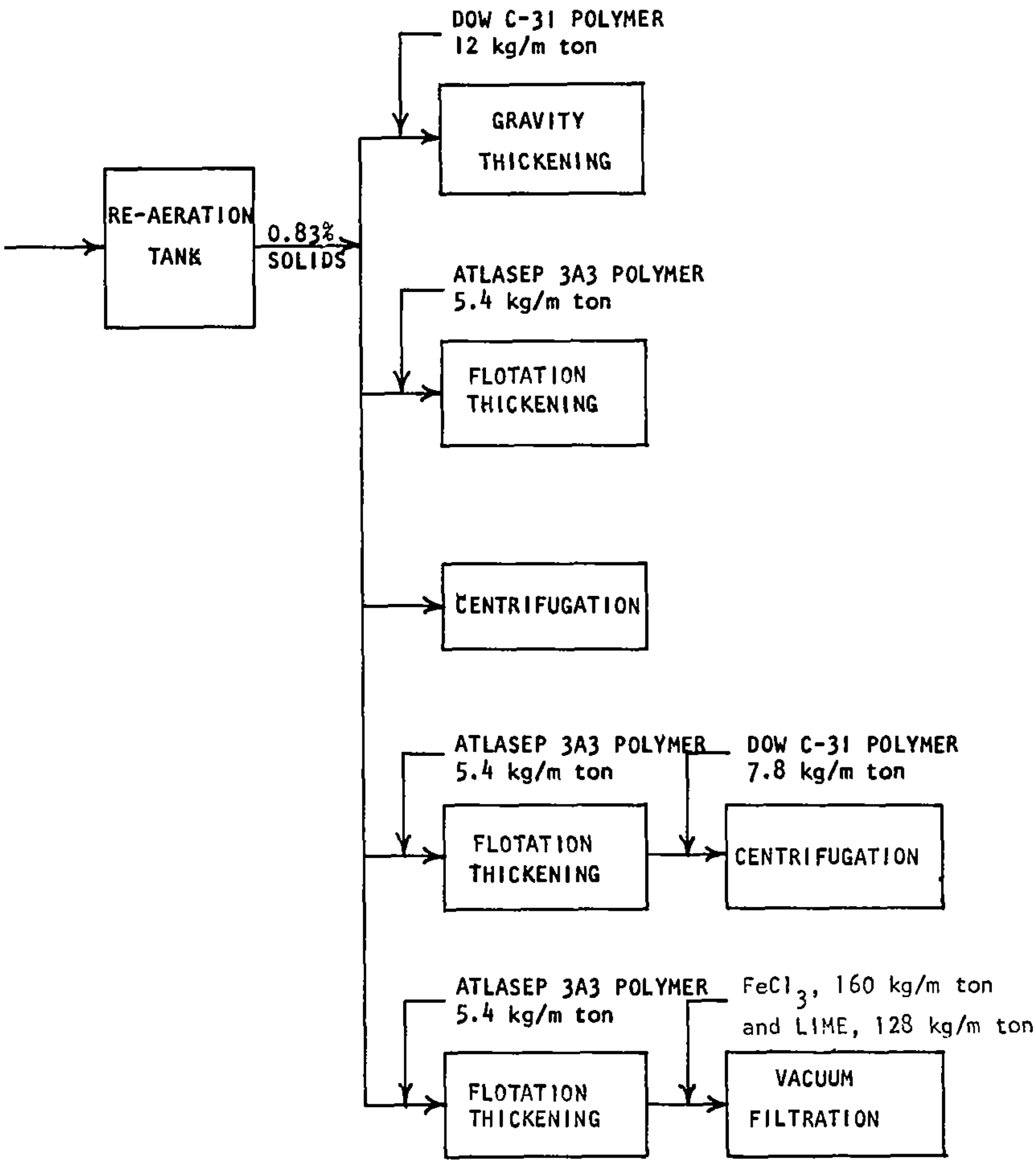

Figure 21. Kenosha, WI - Bench-Scale Dewatering Tests

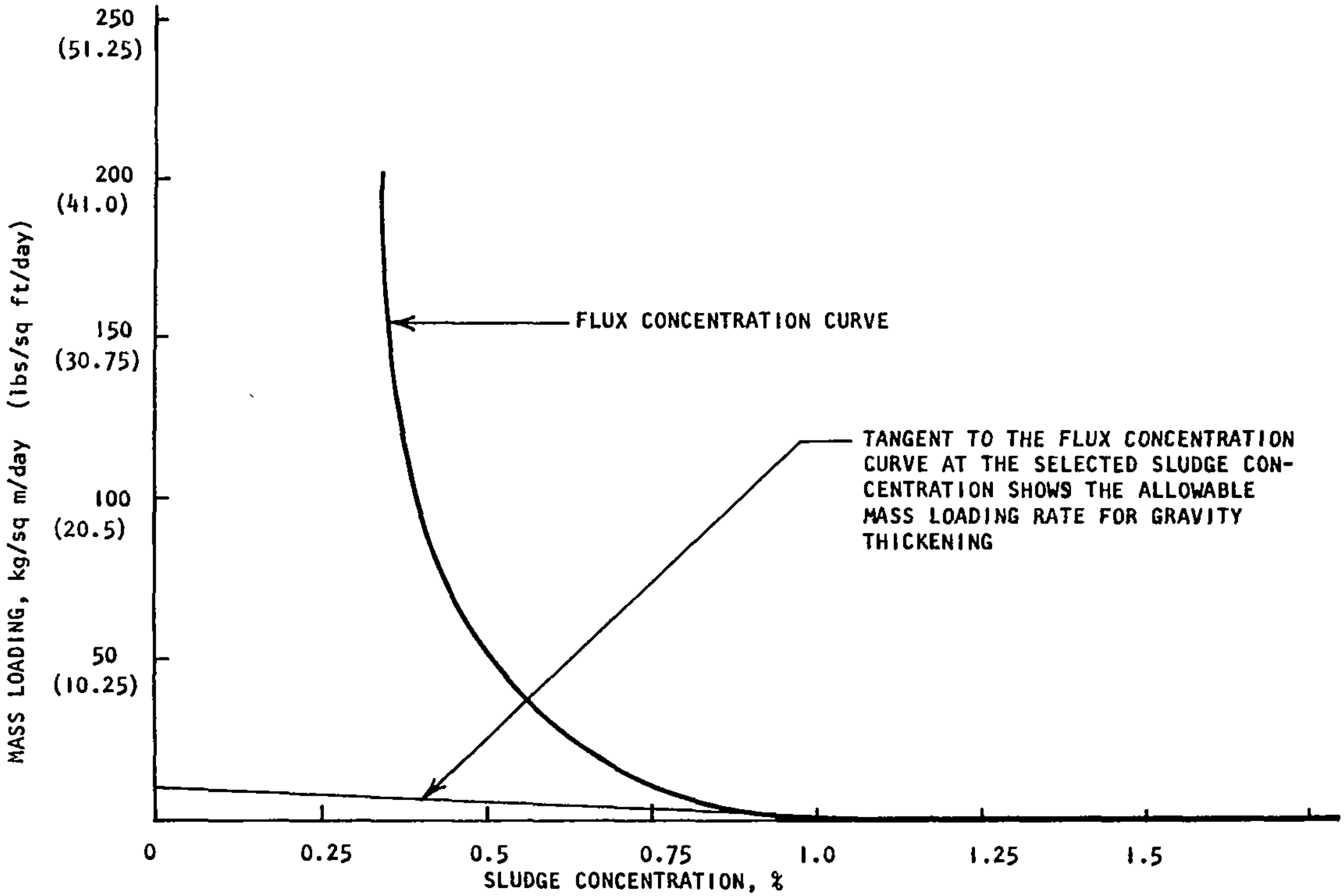

Figure 22. Flux concentration curve for Kenosha, WI, contact stabilization sludge (without chemicals)

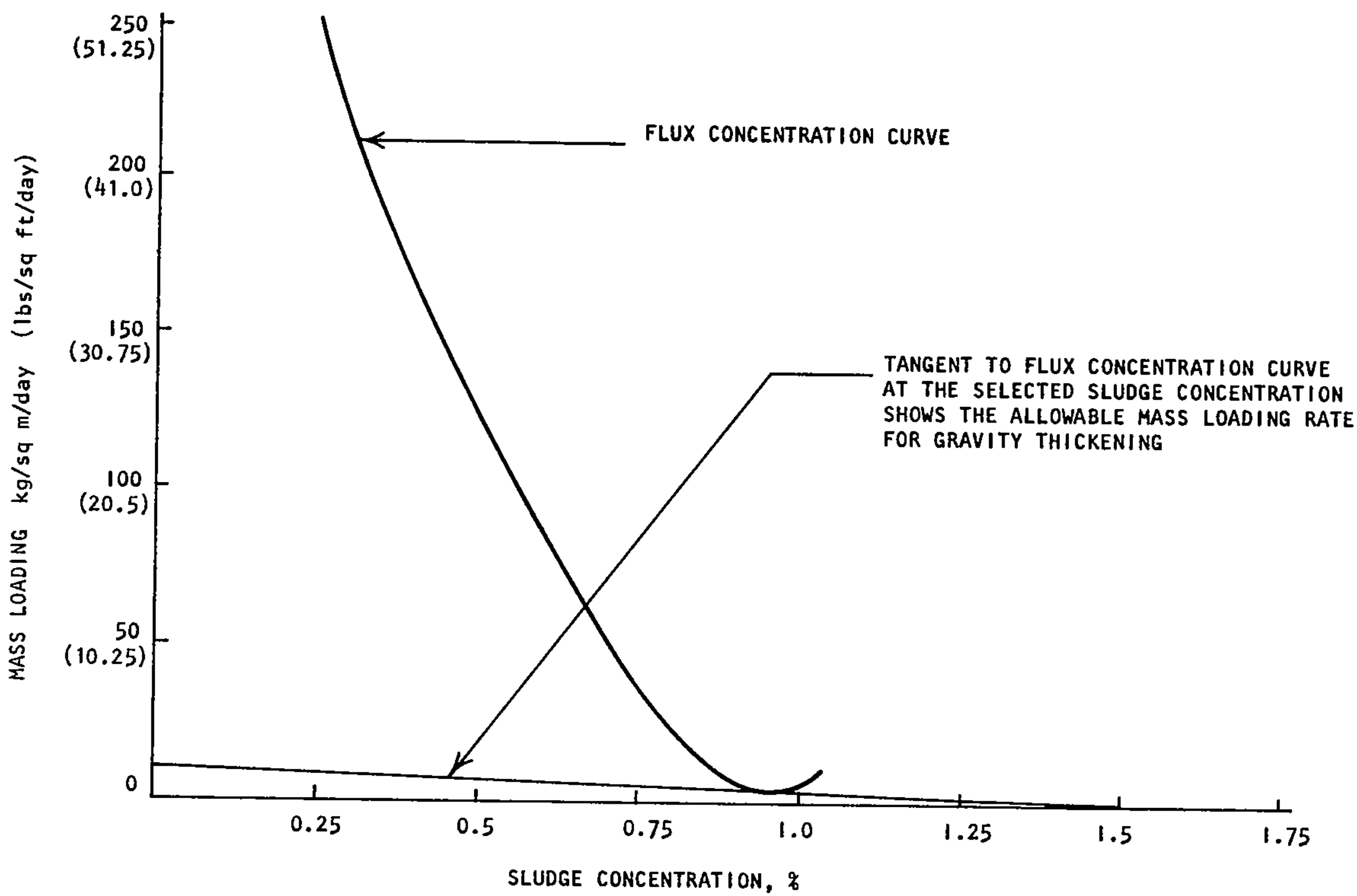

Figure 23. Flux concentration curve for Kenosha, WI, contact stabilization sludge (with DOW C-31 polymer, 11-12 kg/m ton)

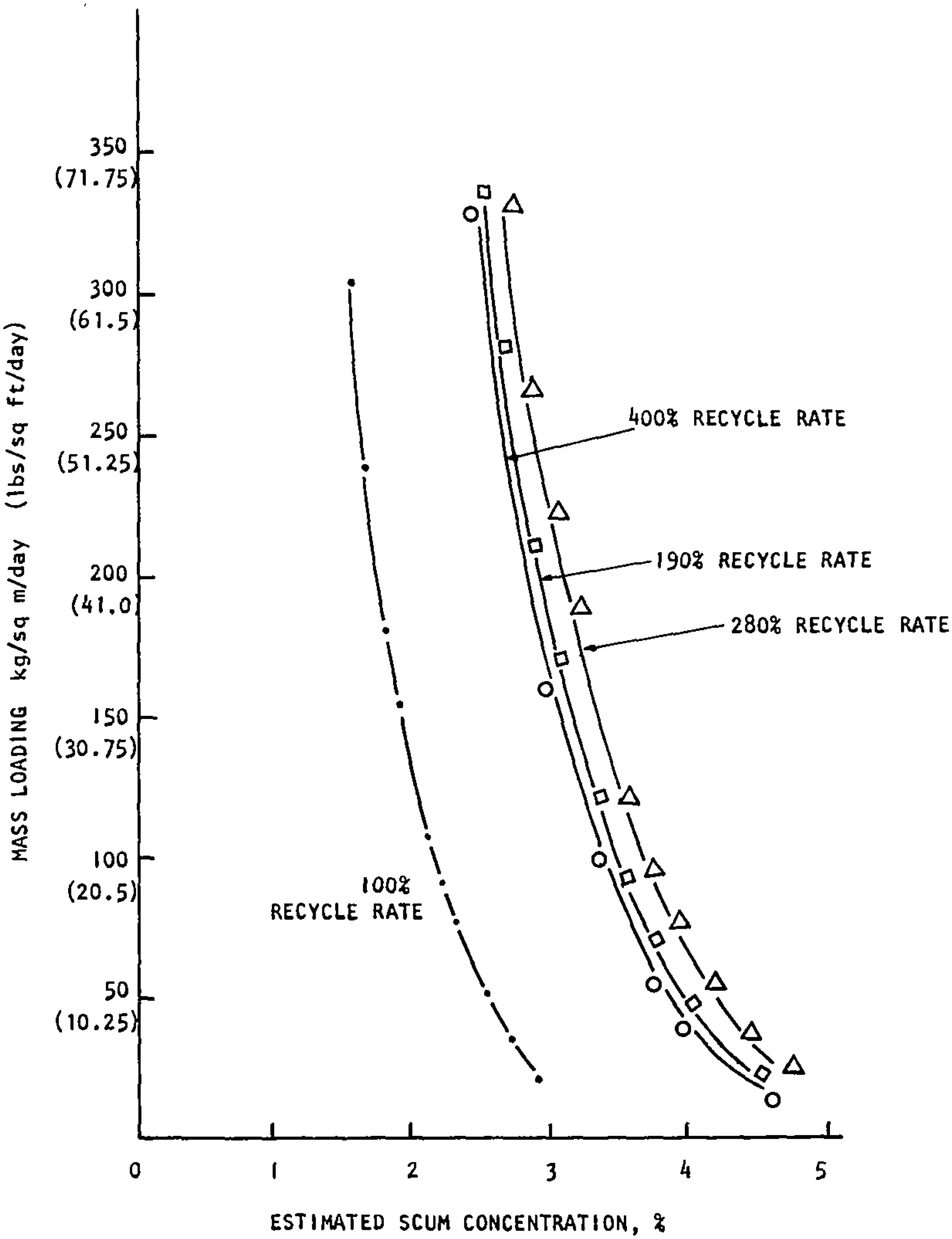

Figure 24. Flotation thickening test results for Kenosha, WI, contact stabilization sludge (without chemicals)

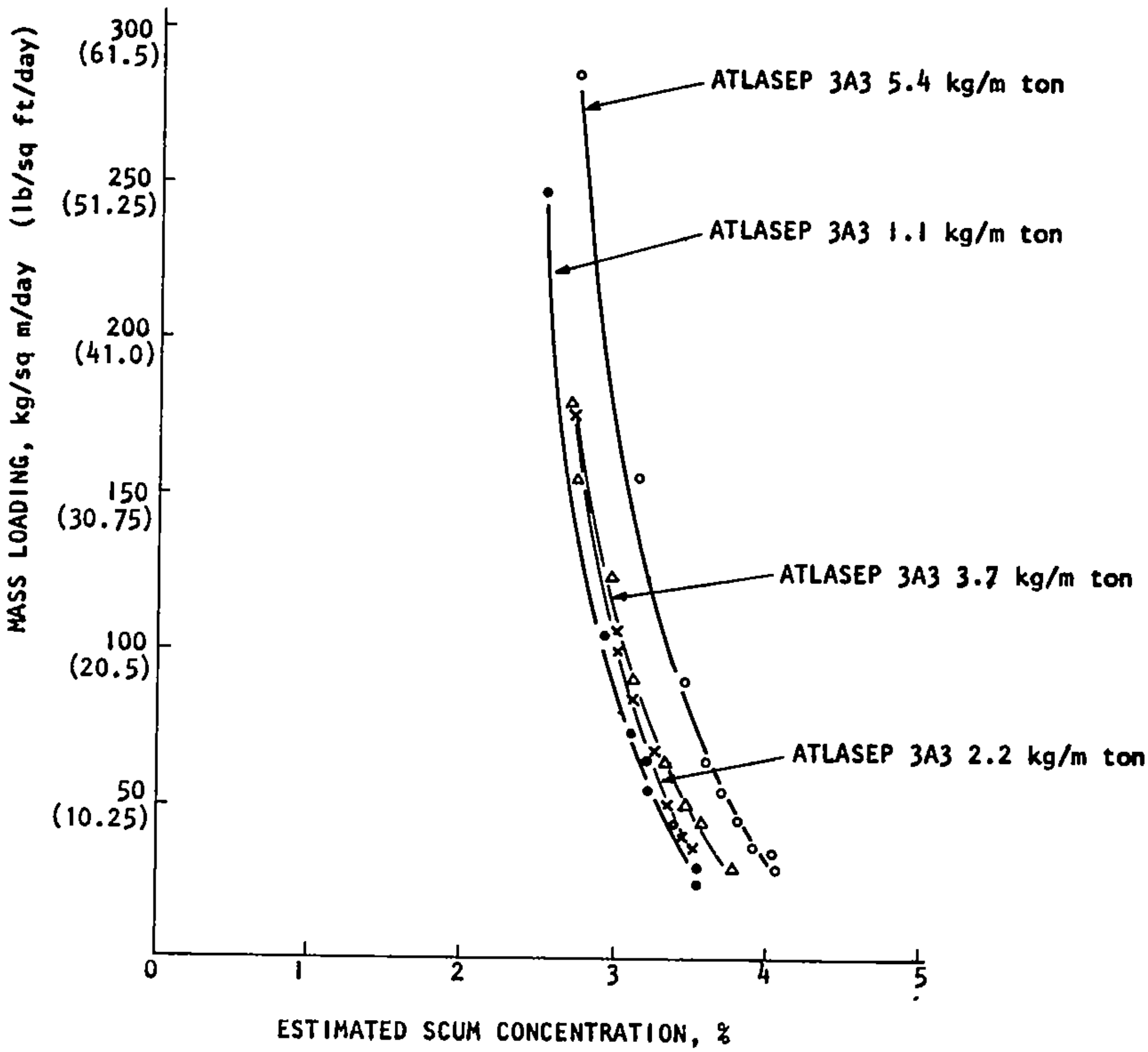

Figure 25. Flotation thickening test results for Kenosha, WI, contact stabilization sludge (with Atlasep 3A3 polymer at 190% recycle rate)

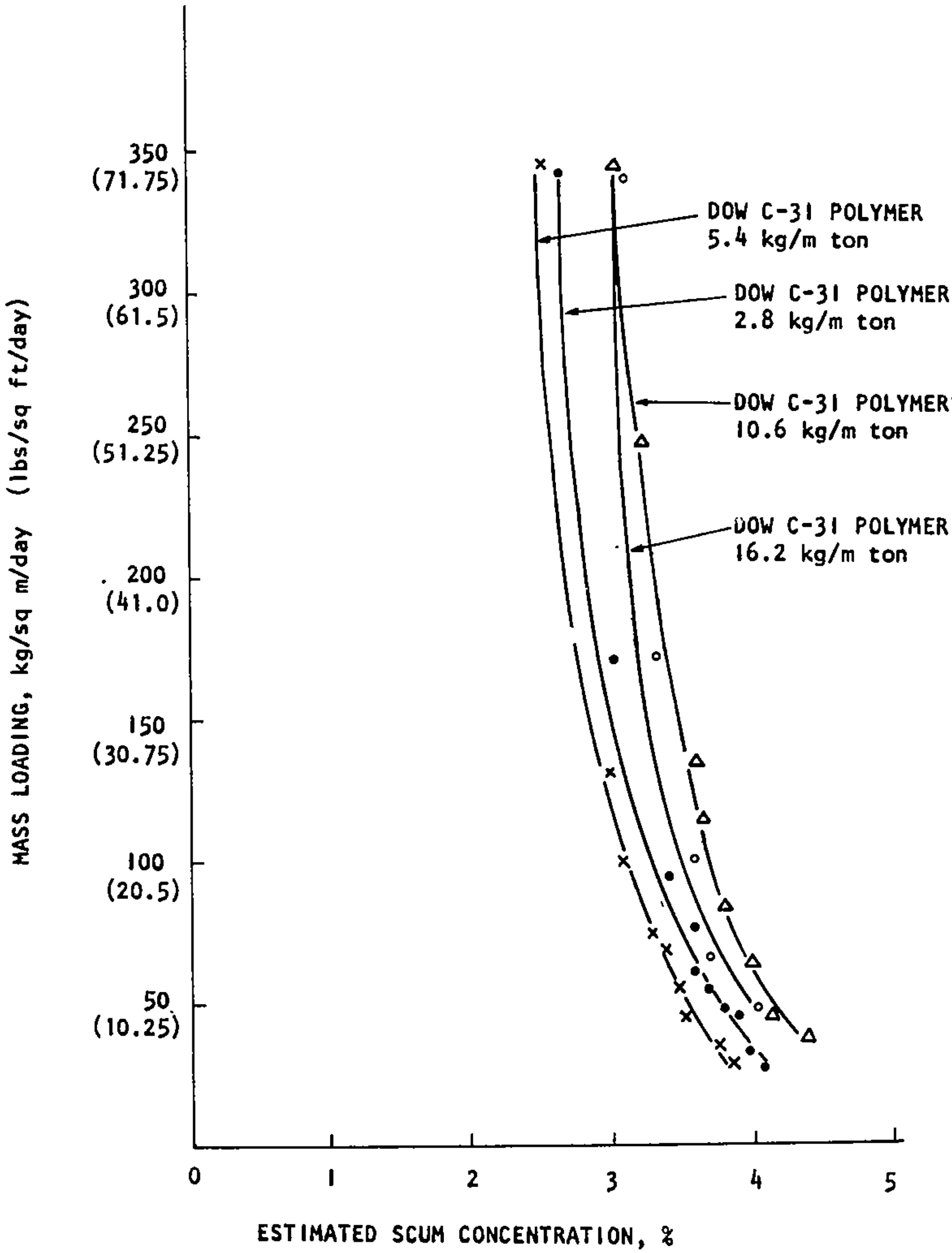

Figure 25 (contd.) Flotation thickening test results for Kenosha, WI contact stabilization sludge (with DOW C-31 polymer at 190% recycle rate)